INTEGRATING COST AS AN INDEPENDENT VARIABLE ANALYSIS WITH EVOLUTIONARY ACQUISITION – A MULTIATTRIBUTE DESIGN EVALUATION APPROACH

THESIS

Marc Trevor Lewis, Captain, USAF

AFIT/GCA/ENV/03-05

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense or the U. S. Government.

AFIT/GCA/ENV/03-05

INTEGRATING COST AS AN INDEPENDENT VARIABLE ANALYSIS WITH EVOLUTIONARY ACQUISITION – A MULTIATTRIBUTE DESIGN EVALUATION APPROACH

THESIS

Presented to the Faculty

Department of Systems and Engineering Management

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Cost Analysis

Marc Trevor Lewis, BS

Captain, USAF

March 2003

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

AFIT/GCA/ENV/03-05

INTEGRATING COST AS AN INDEPENDENT VARIABLE ANALYSIS WITH EVOLUTIONARY ACQUISITION – A MULTIATTRIBUTE DESIGN EVALUATION APPROACH

Marc Trevor Lewis, BS
Captain, USAF

Approved:

Maj Michael A. Greiner, Ph.D. (Chairman)	5 MAR 03 date
Maj Victor D. Wiley, Ph.D. (Reader)	5 MAR 03 date
Michelle Rogers (Reader)	5 March 2003 date

Acknowledgments

First off, I would like to express my thanks and appreciation to my wife. She has sacrificed much to make my graduate education a possibility. Her loyalty, patience, and love remind me every day how lucky I am to have her in my life.

I also need to pass thanks onto my advisor, Maj Michael Greiner, for his direction and encouragement. In addition, I am indebted to the Combat Air Forces Command and Control Systems program office for their sponsorship and support. Finally, I would like to recognize the remainder of my thesis committee, Maj Victor Wiley and Ms. Michelle Rogers, for their guidance, perspective, and enthusiasm.

Marc Trevor Lewis

Table of Contents

Page

List of Figures

Figure Page

List of Tables

Table Page

Abstract

Guidance from the Under Secretary of Defense for Acquisition, Technology, and Logistics (USD(AT&L)) requires 100 percent of defense programs to incorporate cost as an independent variable (CAIV) and evolutionary acquisition (EA) plans within their management baselines. Historically, these two concepts have been implemented independent of one another. In reality, CAIV and EA are tightly coupled. Integration of these two initiatives enables warfighters and developers to better allocate constrained resources, respond to fluctuations in program funding, and plan for future development activities.

This research creates a decision tool to assist the DoD acquisition community in satisfying the intent of the USD(AT&L) guidance. Using multiattribute design evaluation techniques, a core CAIV model is formulated. Next, the core model is expanded to incorporate the dominant features of EA. The expanded model seeks to optimize overall utility across a horizon of multiple development increments. Additionally, technical risk factors are integrated to discount the realized level of attainment for design attributes. Using a DoD command and control system development as the case study, the fully formulated CAIV/EA model is implemented and in a PC spreadsheet. An optimization application solves the mathematical program for a series of cost constraints. The resulting data are collected and translated into a variety of graphics. Sensitivity analysis is performed to understand the response caused by variations in the model's parameters. Model limitations are discussed and recommendations for further investigation are presented.

INTEGRATING COST AS AN INDEPENDENT VARIABLE ANALYSIS WITH EVOLUTIONARY ACQUISITION – A MULTIATTRIBUTE DESIGN EVALUATION APPROACH

I. Introduction

Background

On November 27, 2001 the newly appointed Under Secretary of Defense for Acquisition, Technology, and Logistics (USD(AT&L)), the Honorable E.C. Pete Aldridge delivered testimony to the Commission on the Future of the U.S. Aerospace Industry. Enacted under Section 1092 of the Floyd D. Spence National Defense Authorization Act for Fiscal Year (FY) 2001, the Commission was formed to study the future of the United States aerospace industry in the global economy, particularly in relationship to United States national security (Heuttner, 2001). With over $60 billion in defense related procurement, $40 billion in research and development efforts, and another $40 billion in services, spares, and logistics support, the Under Secretary did not embellish when he stated, "My office has a significant impact on the direction, health, and operations of the aerospace industry" (Aldridge, 2001).

According to the Commission's charter, its mission was broadly stated:

> The Commission shall develop and recommend a series of public policy reforms which will permit the U.S. aerospace industry to create superior technology, excel in the global marketplace, profit from investments in human and financial capital, benefit from coordinated and integrated government decision-making, assure our national security, access modern infrastructure, and give the United States a capacity throughout the 21st century to reach for the stars (Heuttner, 2001).

Pursuant this cause, at the hearing Aldridge presented his "Five Goals." The Under Secretary testified, "I believe (these five goals) will have a direct effect and

significant influence on the outcome of your task" (Aldridge, 2001). Briefly, Aldridge's stated goals for USD(AT&L) were as follows:

- Improve the credibility and effectiveness of the acquisition, technology, and logistics support process.

- Revitalize the acquisition, technology, and logistics workforce.

- Improve the health of the defense industrial base.

- Rationalize our weapon systems and infrastructure with the new defense strategy.

- Initiate those high leverage technologies that will provide the warfighting capabilities and strategies of the future (Aldridge, 2001).

Early the following year, in a memorandum to the service secretaries, Aldridge stated, "In order to guide and measure our progress toward accomplishing these goals, I have established a set of metrics, some of which I plan to report on to the Secretary of Defense" (Aldridge, 2002a:1). The initial set of metrics approved by the Under Secretary pertained to the first goal: improving the credibility and effectiveness of the acquisition, technology, and logistics support process. At the Aerospace Commission hearing the previous November, Aldridge provided additional detail on this goal:

- Too many cost overruns, schedule delays, and performance failures have destroyed our credibility in the eyes of the Congress. Their Constitutionally mandated responsibility for oversight and our lack of credibility leads to the inevitable micromanagement of our acquisition processes;

- Cycle times are too long and the logistics support system cannot yet meet the standards we see for support of commercial systems;

- We are far too optimistic in performance, cost and schedule when we make budget requests and we simply must do a better job of being more realistic in our estimates, even if that means we cannot start as many programs; and

- Reducing cycle time, more realistic cost estimating, spiral development to reduce risk and time, controlling requirements creep,

> and interoperability mandates, are examples of things we can do to re-establish our credibility, and our ability to manage efficiently and effectively (Aldridge, 2001).

Through the memorandum, Aldridge explained how he intended to meet his first goal: "I have approved a metric to require, by the end of FY02, 100 percent of defense programs to incorporate a cost-as-an-independent variable (CAIV) plan and to have an evolutionary acquisition (EA) or spiral development implementation plan in place" (Aldridge, 2002a:1). The memorandum goes on to explain the Department of Defense (DoD) 5000 series (mandatory acquisition guidance) would be adjusted during their next update cycle to reflect these new program management requirements (Aldridge, 2002a:1).

This guidance is significant because it represents the first instance where the concepts of CAIV and EA are cited together in a mandatory acquisition directive. While neither of the two are new initiatives (they both appeared during the acquisition reform of the mid- to late-nineties), historically they have been addressed and implemented independent of one another. To completely understand the ramifications of this guidance, it is important to have a clear understanding of CAIV and EA.

Cost as an Independent Variable (CAIV)

CAIV is a DoD strategy that makes total life-cycle cost, as projected within the acquisition environment, a key driver of system requirements, performance characteristics, and schedules. Simply put, CAIV treats cost as a military requirement. This is a conceptual change in thinking from the days of requirement-, performance-, and sometimes schedule-driven costs (Rush, 1997:161).

In 1995, Under Secretary of Defense for Acquisition and Technology Dr. Paul Kaminski launched a DoD-wide working group to address approaches and measures to

reduce and control weapon system life cycle costs. CAIV is a result of this endeavor.

The working group summarized their findings:

> This strategy entails setting *aggressive*, realistic cost objectives for acquiring defense systems, and managing risks to obtain these objectives. Cost objectives must balance mission needs with projected out year resources, taking into account existing technology as well as high-confidence maturation of new technologies. This concept has become known as "cost as an independent variable" (CAIV), meaning that, once the system performance and objective cost are decided (on the basis of cost-performance trade-offs), the acquisition process will make cost more of a constraint, and less of a variable, while nonetheless obtaining the needed military capability of the system (Kaminski, 1995:3).

Buried within this definition is the central tenet of the CAIV approach: an increased role for the end-user through participation in setting and adjusting program goals throughout the program, particularly in the cost-performance trade-off process. Beyond the definition, the working group also generated a conceptual approach to implement CAIV processes within defense acquisition programs. This approach is characterized by the following aspects:

- Setting realistic but aggressive cost objectives early in each acquisition program.
- Managing risks to achieve cost, schedule, and performance objectives.
- Devising appropriate metrics for tracking progress in setting and achieving cost objectives.
- Motivating government and industry managers to achieve program objectives.
- Putting in place for fielded systems additional incentives to reduce operating and support costs (Kaminski, 1995).

These guidelines summarized Dr. Kaminski's policy and strategy to develop and field affordable weapons systems that are responsive to user needs.

To the casual observer, CAIV should not appear as a revolutionary idea. The prudent consumer only buys what he or she can afford. In our private lives, we constrain our personal acquisitions within our available budgets. We make trade-offs between vacations and car payments, dinners out and purchases at the supermarket, etc. We also look for ways to save money (clipping coupons, carpooling). All of these activities mirror the CAIV guidelines cited above. Unfortunately, prior to the release of the CAIV working group report in 1995 and the incorporation of its recommendations into the DoD 5000 series in 1996, this line of thinking did not permeate the acquisition management community (Rush, 1997:162). As was previously mentioned, defense system acquisitions have traditionally been driven by requirements and performance.

It is also important to note the concepts embodied within CAIV are not unique to the DoD environment. Around the same time Dr. Kaminski and the CAIV working group was preparing to release its guidance, the Consortium for Advanced Manufacturing International (CAM-I) published a book entitled, *Target Costing: The Next Frontier in Strategic Cost Management.* Target costing in the commercial sector is analogous to the public sector's CAIV. While CAIV is a strategic process concerned with managing aggressive cost objectives (within authorized budgets), target costing is a strategic profit and cost management process focused on managing the allowable amount of cost that can be incurred on a product while still earning the required profit from the product.
To clearly describe the commercial counterpart to CAIV, CAM-I provides a concise definition:

> The target costing process is a system of profit planning and cost management that is price led, customer focused, design centered, and cross-functional. Target costing initiates cost management at the earliest stages of product development and applies it throughout the product life

> cycle by actively involving the entire value chain (Ansari and Bell, 1997:3).

The similarities between the two processes are readily apparent. Both place the end-user as their primary focus. Additionally, CAIV and target costing are concerned with establishing cost targets and then making design trade-offs early in the life of a project. Finally, risk is managed throughout the lifecycle so targets (i.e., aggressive cost objectives) are met. The concepts of target costing have permeated private manufacturing sectors. According to Toyota's annual report for 1993, "Cost management is going to be for the automobile industry in the 1990's what quality control was in the 1970s and '80s" (Ansari and Bell, 1997:5). Since embracing best commercial practices is a cornerstone of DoD acquisition reform, it is not surprising USD(AT&L) has mandated CAIV be implemented across all defense system programs.

Evolutionary Acquisition (EA)

EA and spiral development (SD), are two terms continually misused and misinterpreted by the acquisition community. This impression is substantiated by the memorandum released by Aldridge on April 12, 2002. In the memo Aldridge states:

> "Since the publication of DoD Directive 5000.1 and DoD Instruction 5000.2, in which the Department established a preference for the use of EA strategies relying on spiral development, there has been some confusion about what these terms mean and how spiral development impacts various processes such as contracting and requirements generation that interface with an EA strategy. The purpose of this memorandum is to address those questions" (Aldridge, 2002b:1).

Aldridge provides a clear, concise definition of these terms and explains the interrelations between the concepts.

EA is an acquisition strategy that defines, develops, produces or acquires, and fields an initial hardware or software increment (or block) of operational capability. This strategy is based on technologies demonstrated in relevant environments, time-phased requirements, and demonstrated manufacturing or software deployment capabilities. These capabilities can be provided in a shorter period of time, followed by subsequent increments of capability over time that accommodate improved technology and allow for full and adaptable systems over time. Each increment will meet a militarily useful capability specified by the user (i.e., at least the thresholds set by the user for that increment); however, the first increment may represent only 60 to 80 percent of the desired final capability (Aldridge, 2002b:1).

According to the USD(AT&L) definition, there are two basic approaches to EA. In one approach the ultimate functionality can be defined at the beginning of the program, with the content of each deployable increment determined by the maturation of key technologies. In the second approach, the ultimate functionality cannot be defined at the beginning of the program, and each increment of capability is defined by the maturation of the technologies matched with the evolving needs of the user. In both cases, an increment is considered a militarily useful and supportable operational capability that can be effectively developed, produced or acquired, deployed, and sustained. Each increment of capability will have its own set of thresholds and objectives set by the user (Aldridge, 2002b:1).

Often, the terms EA and SD are used interchangeably. The memorandum attempts to delineate between the two by providing a separate definition for the later. SD is an iterative process for developing a defined set of capabilities within one increment.

This process provides the opportunity for interaction between the user, tester, and developer. In this process, the requirements are refined through experimentation and risk management, there is continuous feedback, and the user is provided with the best possible capability within the increment. Each increment may include a number of spirals. Spiral development implements EA (Aldridge, 2002b).

Integrating CAIV and EA

The brief review of the concepts of CAIV and EA reveals there is cause for Under Secretary Aldridge requiring managers of defense acquisitions to generate corresponding plans for their respective programs (as expressed in the January 19, 2002 memorandum). CAIV and EA are tightly coupled. The most apparent linkage is the role the user plays in each. Within CAIV, the user is a pivotal player in the cost-requirements-performance trade-off process. Additionally, as the fiduciary advocate for the program (the one who submits budget requests into the DoD planning, programming, and budgeting system (PPBS)), the user must also participate in the creation of aggressive cost objectives. From an EA perspective, the user must define the system's core and incremental capabilities. Additionally, the user must describe the threshold and objective levels of performance for these capabilities. All of these activities are dependent upon one another. Changes made to capabilities create ripples affecting cost. Aggressive cost objectives and their ensuing trade-offs have profound effects upon the system's capabilities, its schedule, and what is ultimately delivered to the user.

Research Questions

The guidance provided in the January 19, 2002 USD(AT&L) memorandum explicitly requires program managers to create separate implementation plans for CAIV and EA respectively. However, because of the apparent connection between the two activities, the challenge of creating two, independent plans is futile. Any perturbation made to one impacts the other. This scenario begs the question, "Is it possible to develop a process that integrates CAIV objectives with the EA framework?" If so, this process would enable users and developers to better:

- Allocate constrained resources,
- Respond to fluctuations in program funding, and
- Plan for future development activities (i.e., increments).

This research endeavors to create a process/model to assist program managers, cost analysts, engineers, and users to meet the first goal set by Under Secretary Aldridge: achieving credibility and effectiveness in the acquisition and logistics support process. Along the way, this research will explore the following questions:

1. How might one generate and graphically depict the relationship between system cost and performance for a defense program?
2. What is the marginal benefit (or detriment) to a weapon system's performance given an increase (or decrease) in funding beyond a cost objective?
3. How might one optimally allocate resources across a program planning horizon spanning several increments?

Research Overview

This chapter has explored the underlying requirement for a process that integrates CAIV with EA. USD(AT&L) has stated all defense programs must have plans for each.

However, creating plans independent of one another will most likely not meet the intent of the Under Secretary's goal. Ultimately, a new model is necessary. This research will explore the development of such a model using a notional Air Force ground based command and control (C2) system as a test case.

Chapter II develops more complete definitions for both CAIV and EA. The chapter also explores their foundations in DoD acquisition guidance. Next, a survey of popular approaches used to implement these initiatives (independent of one-another) is presented. Finally, some time is spent reviewing candidate analytical techniques for use in the formulation of the CAIV/EA model.

Chapter III introduces the methodology used to create an integrated CAIV/EA model. First, the core CAIV model is formulated. Following this formulation, the model is expanded to incorporate features associated EA. Finally, potential strategies for model evaluation and analysis are discussed.

Chapter IV integrates the model developed in the previous chapter with the notional ground based C2 system. The characteristics of the notional C2 system are applied to the model. The model is then completely implemented and exercised. The results from these activities are collected and analyzed. Finally, the behavior of the CAIV/EA model is evaluated through the use of sensitivity analysis.

Chapter V summarizes the outcomes of the research questions explored. The chapter also presents the limitations of the research. Finally, the chapter presents opportunities for further study on this subject.

II. Literature Review

Overview

Research by RAND identifies two dominating feature of the modern U.S. market for weapons and weapons systems:

- First, it is characterized by a single buyer, the DoD, which defines the product and controls the sales opportunities of weapon system providers;
- Second, it is distinguished by a higher degree of technical complexity and innovation than most commercial markets (Lorell et al., 2000:13-14).

With regards to this first feature, the weapons market model clearly diverges from a commercial market model; where diverse and autonomous buyers choose products offered by competitive sellers on the basis of their price and performance characteristics. The second feature compounds the differences. Developers of new weapons systems frequently push the limits of known technology, incorporating designs and materials that are largely unproven. In contrast, most commercial product developers tend to improve incrementally on existing technologies (Lorell et al., 2000:14).

In the mid-1990s, the problems of declining defense budgets and growing weapons system procurement costs lead some government and industry officials to advocate the integration of the U.S. military and civilian industrial bases, a concept commonly referred to as Civil-Military Integration (CMI) (Lorell et al., 2000: 1). Advocates of CMI attributed the aforementioned problems to the unique features of the U.S. weapons markets. They believed that DoD adoption of commercial business practices and a more commercial-like market structure would spur the development of

high-performance weapon systems at lower costs than could be achieved under the current heavily regulated acquisition process (Lorell et al., 2000: 2).

The current round of acquisition reform (AR), begun early in the Clinton administration, has made CMI a centerpiece (Lorell and Graser, 2001: 3). Two initiatives closely linked with CMI are EA and CAIV. This chapter begins with a discussion of EA and the methods used to implement this strategy. Next, CAIV analysis and the techniques available for its execution are reviewed. Finally, the chapter presents a brief overview of Utility Theory and its application to decision problems characterized by multiple decision attributes.

Implementing EA

To summarize the definition provided in the previous chapter, EA is characterized by:

- Incremental delivery of operational capability,
- Time phased requirements based upon technological maturity and availability of resources,
- Shorter cycle times, and
- Adaptable, open systems (Aldridge, 2002b:1).

While this definition helps to provide an initial mental picture of EA, more detail is necessary to completely describe the concept.

It is valuable to understand the initial conditions which led to the genesis of EA. The *Joint Logistics Commanders Guidance for Use of EA to Acquire Weapon Systems* was published in 1987 (with a re-issue in 1998) in response to "A clearly discernable need to reduce the time necessary to field (weapons) systems – a need driven by the rapid

acceleration in technologies used in such systems" (DSMC, 1998:vii). This document cites the results of two major studies[1], which found the use of the standard acquisition approaches (described in Department of Defense Directives (DoDD) and Instructions (DoDI)) have often led to unsatisfactory results (DSMC, 1998:2-1). As the studies revealed, these difficulties arose primarily because it was often "impossible to define detailed operational capabilities or functional characteristics for the complete system before undertaking full scale development" (DSMC, 1998:2-1). Additionally, whenever the development effort is begun without clear definition of system operational concepts, capabilities, and functional characteristics, "It is very likely that the development process will be long, costly, and unstable. Consequently, the developed system will be unsatisfactory and logistically unsupportable"
(DSMC, 1998:2-1).

External pressures stimulated the need to change the standard DoD acquisition approach as well. These pressures are political, economic, and technological in nature:

- The emphasis on the European continental threat, the Soviet Union, has been replaced by multiple and constantly changing threats;

- A fiscally constrained economy results in fewer new system starts, more emphasis on modifications to current systems, and the use of non-developmental items (NDI); and

- The shortened period of technological advances, and the ready market availability of commercial off-the-shelf (COTS) components, change the potential to make performance trade-offs and provides opportunities to achieve cost and schedule improvements (DSMC, 1998:2-2).

[1] "Report of the Defense Science Board Task force on Command and Control Systems Management", July 1978, Office of the Under Secretary of Defense Research and Engineering, Washington D.C. and "Command and Control (C2) Systems Acquisition Study Final Report", September 1, 1982, The Armed Forces Communications and Electronics Association, Falls Church, Virginia.

In light of these findings, the aforementioned studies "have recommend the use of an EA strategy to permit orderly, timely, and efficient development of effective defense systems for the type of environment in which new defense acquisitions will be operated and maintained" (DSMC, 1998:2-2).

Faced with mounting pressure, the DoD has responded. The most recent version of DoDI 5000.2 *Operation of the Defense Acquisition System* articulates current guidance on acquisition strategy development. The document states:

> "The acquisition strategy shall define not only the approach to be followed in System Development and Demonstration, but also how the program is structured to achieve full capability. There are two such approaches, evolutionary and single step to full capability. An evolutionary approach is preferred" (DOD, 2001a:4.7.3.2.3.3.1).

In line with the DoD guidance, the services have also adopted EA as the preferred acquisition approach. Specifically, the Air Force has formalized an EA policy within Air Force Instruction (AFI) 63-123, *EA for C2 Systems*. This AFI guides and directs the use of EA strategy using a spiral development process in support of the acquisition of C2 systems. It is important to note that EA is not solely applicable to this family of systems. However, the approach is particularly useful when software is a key component of the systems, and software is required for the system to achieve its intended mission (DOD, 2001a:4.7.3.2.3.3.1).

The AFI reiterates the findings of the previous studies and expands upon the need for a tailored EA approach:

> "Traditional DoD acquisition processes developed during the cold-war era were oriented toward larger systems designed for unique military requirements and are not often suitable for today's rapid technology changes and continuous requirement refinement" (DAF, 2000a:2).

In short, EA addresses the volatility and risks associated with modern weapons system development and acquisition efforts. Potential sources of volatility and risk include:

- Uncertainty about details or maturity of requirements,
- Continuous user input and feedback,
- Shortened technology insertion life-cycles,
- Schedule urgency,
- Budget and/or cost uncertainty,
- Technical maturity, and
- Feedback from test, evaluations, experiments, and exercises (DAF, 2000a:2).

EA mitigates volatility and risk by allowing an acquisition program to respond to changing conditions, enabling each increment to accommodate the following three activities: 1) develop new capabilities supporting the operational requirements and goals of the system, 2) exploit opportunities to insert new technologies that reduce cost of ownership or accelerate fielding of new capabilities resulting from experimentation or technology demonstrations, and 3) refine current capabilities based on user feedback, testing, or experimentation (DAF, 2000a:3.3).

The spiral development process drives the capabilities and characteristics of each EA increment. A high-level definition of this process is as follows:

> "The spiral development model is a risk-driven process model that is used to guide multi-stakeholder concurrent engineering of software-intensive systems. It has two main distinguishing features. One is a cyclic approach for incrementally growing a system's degree of definition and implementation while decreasing its degree of risk. The other is a set of anchor point milestones for ensuring stakeholder commitment to feasible and mutually satisfactory system solutions" (Boehm, 2001:2).

Figure 1 presents a graphical depiction of the spiral development model. The cyclic nature of the spiral model is discussed above. Rather than develop the completed product in one step, multiple cycles are performed with each taking steps calculated to reduce the most significant remaining risks (Boehm, 2001: 2). The goal of spiral development is to allow innovation in technology and operational concepts to occur simultaneously and continuously at many levels and across all functional lines. The result is operational requirements evolving in parallel with system capabilities through "An iterative process of idea generation, rapid prototyping, technology insertion, and operational testing" (DAF, 2000a:4.1.2).

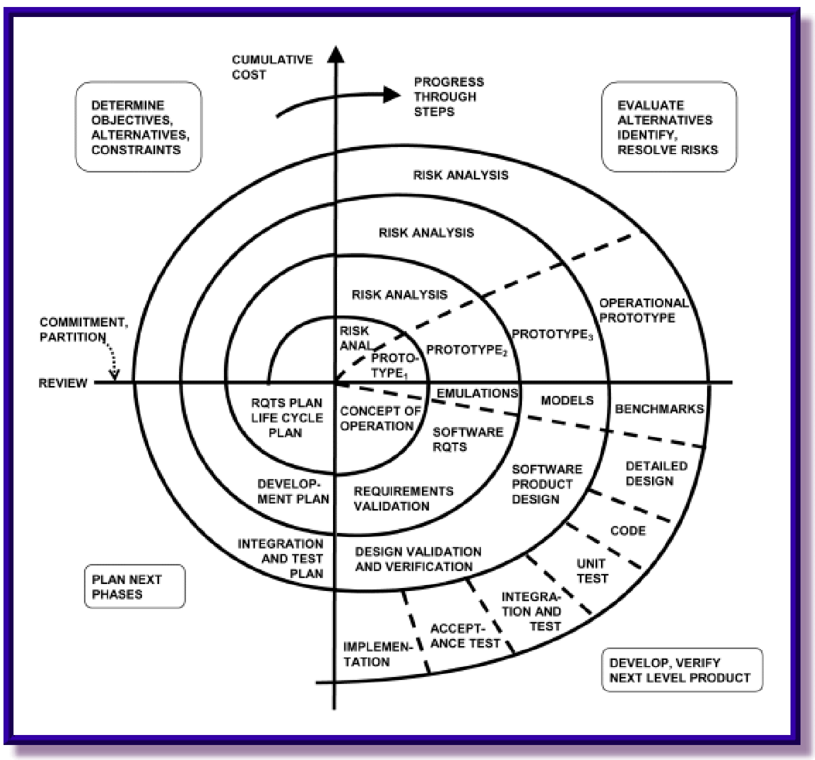

Figure 1. Spiral Development Process (Boehm, 2001)

Prior to employing the spiral development model, it is imperative to establish the following program attributes:

- A general description of the functional capability desired for the final system.[2]
- A concise statement of operational concepts for the final system.
- A flexible, well planned overall open-system architecture.[3]
- A plan for incrementally achieving the desired total capability that adheres to life-cycle cost effectiveness.
- Continual dialogue and feedback among users, developers, supporters, and testers (DAF, 2000b: 8).

The rationale for mandating these attributes relates back to the anchor point milestones cited in the definition of the spiral development model. Each anchor point milestone is a specific artifact or condition that must be attained at some point. These milestones serve as commitment points and progress checkpoints. They impel the project toward completion (Boehm, 2001: 3). The aforementioned programmatic attributes form the basis for the anchor point milestone reviews.

The three spiral development model anchor points are as follows:

- **LCO** (Life Cycle Objectives) – what should the system accomplish?
- **LCA** (Life Cycle Architecture) – what is the structure of the system?
- **IOC** (Initial Operating Capability) – the first released version.

The focus of the LCO review is to ensure there is a viable business case. The focus of the LCA review is to commit to a single detailed definition of the project. The project must have either eliminated all significant risks or put in place an acceptable risk management plan. The LCA milestone is particularly important, as its pass/fail criteria enable

[2] The lack of specificity and detail in identifying the *final* system capability distinguishes EA from other incremental strategies (e.g., pre-planned product improvement (P3I)) (AFEA Guide, 2000: 8).
[3] The system architecture defines the partitioning of system components, flow of data, flow control, timing, through put relationships, interface layering, and protocol standards. A flexible architecture requires long-term tolerance of change (AFEA Guide, 2000: 8).

stakeholders to hold up projects attempting to proceed into evolutionary or incremental development without life-cycle architecture (Boehm, 2001: 8). The focus of the IOC review is to ensure the project is ready for operations. Together, the anchor point milestones avoid "analysis paralysis", unrealistic expectations, requirements creep, architectural drift, COTS shortfalls and incompatibilities, unsustainable architectures, traumatic cutovers, and useless systems (Boehm, 2001: 8).

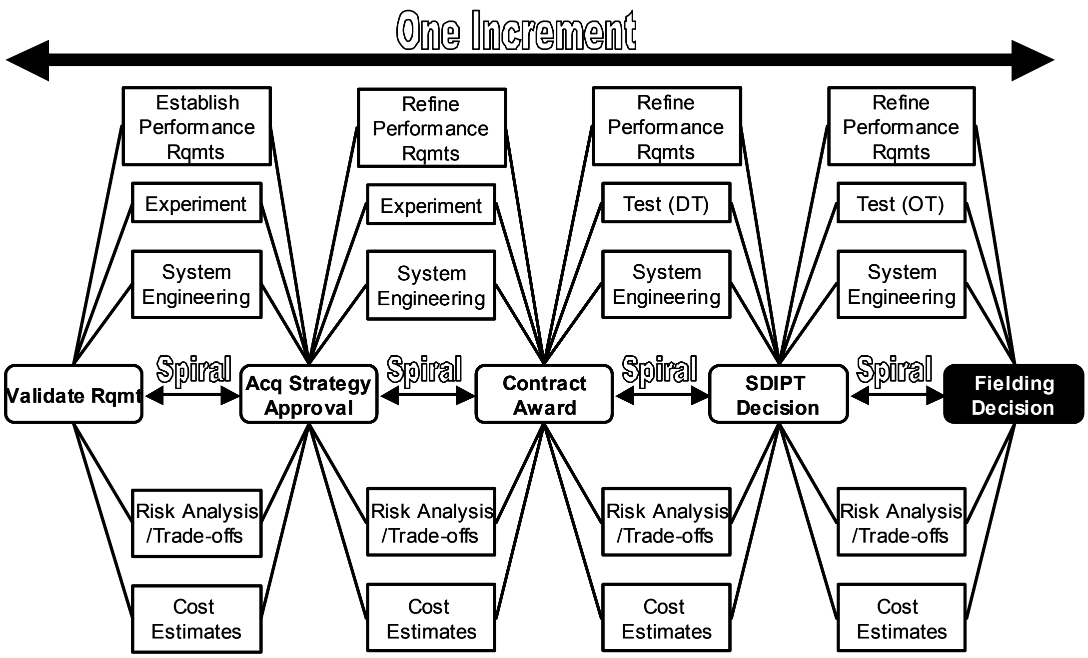

Figure 2. Notional Spiral Development Model (DAF, 2000a)

Figure 2 presents AFI 63-123's notional implementation of the spiral development model. As prescribed by the model, the capabilities and characteristics of an increment are defined in an iterative fashion. Rather than developing the entire increment in one step, multiple cycles (or spirals) are performed with each cycle taking calculated steps to reduce the most significant remaining risks (Boehm, 2001:2). Additionally, the increment's operational requirements evolve in parallel with system capabilities through this process. The "Feedback" nodes are consistent with the spiral

development model's anchor point milestones. These decisions are comparable to LCO, LCA, and IOC artifacts, serving as commitment and progress checkpoints. The outcomes/decisions from the feedback nodes impel the increment forward.

Figure 2 portrays the spiral development model applied to a single increment. However, EA is characterized by the early fielding of an initial (core) capability, enhanced though the delivery of *additional* increments. These additional increments ultimately contribute to a final system capability (DAF, 2000b:7). As previously mentioned, one of the necessary programmatic attributes is a cost effective, life-cycle plan for incrementally achieving the desired total capability. Again, a major goal of the EA strategy is to deliver an operationally useful and supportable capability to the user quicker than traditional strategies. Therefore, this plan must focus on early fielding of capability by using mature, well-understood technologies (and requirements) for the core while saving higher risk activities for the latter increments (DAF, 2000b:27). This aspect of EA necessitates operational requirements to be time phased.

Table 1 presents a graphical depiction of time-phased operational requirements for a notional weapons system. The first column contains the designation for each of the performance parameters. Performance parameters are system capabilities or characteristics that describe what the user expects from the system in order to perform the mission and satisfy the mission requirement. The second column designates whether or not a performance parameter is a key performance parameter (KPP). KPPs are those capabilities and characteristics considered most essential for successful mission accomplishment (DAF, 2000b:25). The third column describes performance parameter levels. A threshold is a minimum acceptable value for a system capability or

characteristic that, in the user's judgment, is necessary to provide the operational capability that satisfies the mission need. An objective is a value beyond the threshold that could have a measurable and beneficial impact on the system capability, supportability, or operational concept of employment (DAF, 2000b:25). The remaining columns specify the capabilities and characteristics for each of the EA increments. The operational requirements are phased appropriately across the horizon of increments so the core provides an initial, operationally-useful capability through the use of readily available technologies. The latter increments address other higher risk requirements.

Table 1. Time Phased Operational Requirements (DAF, 2000b)

Performance Parameters	Key Performance Parameters	Objective or Threshold	Core	Increment 1	Increment 2	Increment 3
1	X	Objective			X	
		Threshold	X			
2	X	Objective				X
		Threshold		X		
3		Objective		X		
		Threshold	X			
4		Objective				
		Threshold				X
5	X	Objective			X	
		Threshold	X			

Another method for visualizing time-phased requirements is through the use of a Venn diagram and a simplified Gantt chart. The Venn diagram in Figure 3 illustrates how the various increments combine to deliver the total operational capability for a notional weapon system. The Gantt chart presents a timeline for the execution and delivery of each increment. It is important to note, the spiral development process described by Figure 2 takes place within each of the rectangular increments in Figure 3. The equations depict the logical relationship between the operational requirements and

the increments. For example, the core increment addresses the threshold level for KPP 1, the threshold level for KPP two, and so on. The summation of the individual increments equates to the total operational capability documented within the EA operational requirements document (ORD). Using the spiral development process model, the ORD begins its life as a general description of the functional capability desired for the final system. However, after successive spirals and increments, the ORD becomes increasingly more detailed.

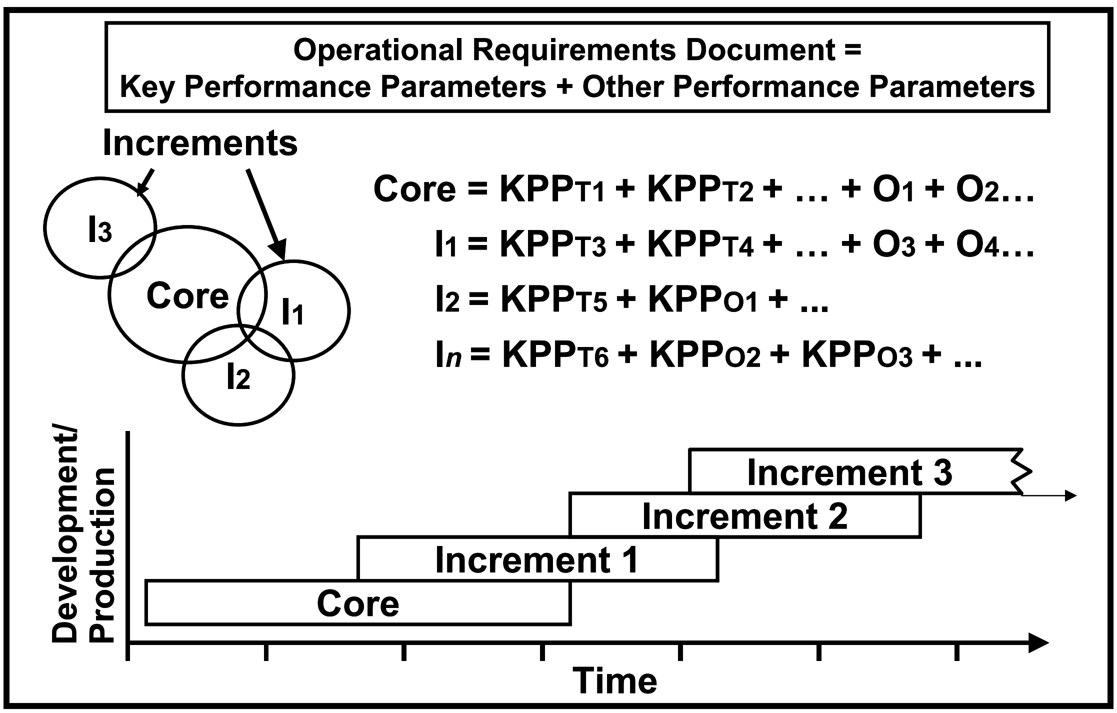

Figure 3. Graphical Representation of Time Phased Requirements (DAF, 2000b)

While there are more aspects to the implementation of an EA strategy (e.g., contracting considerations, operational testing, etc.), the previous discussion provides the level of detail needed for the scope and direction of this research. It is now necessary to review the methods available to implement CAIV analysis.

Implementing Cost as an Independent Variable Analysis

As defined in the previous chapter, CAIV is a DoD strategy that makes total life-cycle cost as projected within the acquisition environment a key driver of system requirements, performance characteristics, and schedules (Rush, 1997:162). The Defense Acquisition Deskbook supplies a broader description:

> "CAIV is a strategy that entails setting aggressive, yet realistic cost objectives when defining operational requirements and acquiring defense systems and managing achievement of these objectives. Cost objectives must balance mission needs with projected out-year resources, taking into account existing technology, maturation of new technologies and anticipated process improvements in both DoD and industry" (Kaminski, 1995:3).

DoD Document 5000.2-R, *Mandatory Procedures for Major Defense Acquisition Programs (MDAPS) and Major Automated Information Systems (MAIS) Acquisition Programs* has cemented this way of thinking within DoD acquisition policy. Per this document, "The user shall treat cost as a military requirement. The acquisition community, including technology and logistics, and the requirements community shall use the CAIV process to develop total ownership cost (TOC), schedule, and performance thresholds and objectives" (DOD, 2001c:C1.3.1).

RAND cites CAIV as being, "Probably the single most important element for carrying out the transformation to commercial-like weapon system R&D approach" (Lorell and Grasser, 2001:32). In a multi-year study, RAND evaluated the AR cost saving estimates for eleven weapon system programs (to include the Joint Direct Attack Munition (JDAM), Joint Air-to-Surface Standoff Missile (JASSM), and more). Pursuant to this study, researchers looked at the overall impact of CAIV upon weapon system costs. According to RAND, the data suggest that R&D savings in the range of 15 to 35

percent may be possible in certain types of programs that are structured in a commercial-like manner in accordance with CAIV (Lorell and Grasser, 2001:119). However, the researchers qualify these results by stating, "The AR (study) pilot programs are relatively small and are characterized by low technological risk, commercial derivative items, and large production runs. Thus, the scale of potential cost benefits for a large, complex weapon system that employs high-risk, cutting-edge technology remains uncertain" (Lorell and Grasser, 2001:120).

As mentioned previously, the commercial analogue to CAIV is target costing, also referred to as "must cost." Under a "must cost" approach, a commercial developer first conducts market research to determine potential customer requirements and price estimates. Using these data, the developer sets price and profit targets for the finished product. The difference between these two values yields the target or "must cost." The target cost is then distributed to the various product subsystems. The subsystem targets costs are further decomposed and passed along the design and supply chains.

In a survey of aerospace firms that do business in the commercial sector (to include Boeing, Lockheed Martin, Northrop Grumman, et al.), RAND researchers noted the following:

- The "must cost" approach delivers safe, reliable aircraft to the airlines at extremely competitive prices. However, budget-induced design conservatism may also reduce both the size and scope of purely performance related technological innovations in the commercial aircraft industry.

- Under "must cost", commercial carriers are generally not willing to pay for technology innovations that improve the performance of aircraft equipment unless they believe those improvements will contribute to their immediate bottom-line profitability.

- With the move toward incrementalism introduced by “must cost”, performance-centered innovations may be less likely to appear (Lorell et al., 2000:110-11).

In the context of adopting a commercial-like approach to weapon system acquisition, the results from this survey beg an important question. Can system cost be reduced without sacrificing performance? RAND believes that adopting a commercial-like acquisition strategy will prove beneficial to the DoD. The researchers found that binding cost constraints introduced by “must cost” have shifted the focus of commercial aerospace manufacturers from performance to cost. This has not resulted in airliners with poor performance characteristics (in some cases there have been notable improvements) (Lorell et al., 2000:135). However, when adopting a “must cost” approach (i.e., CAIV), the DoD must demand careful program management to sustain technical innovation in the desired areas (Lorell et al., 2000:135).

The “careful program management” cited in the RAND study is manifested by disciplined requirements-cost-performance trades-offs; the essence of CAIV implementation (Rush 1997: 163). According to DoD 5000.2-R, “The best time to reduce TOC and program schedule is early in the acquisition process. Continuous cost / schedule / performance trade-off analysis shall accomplish cost and schedule reductions” (DOD, 2001c:C1.3.3.1). The logic behind CAIV’s emphasis on trade-offs is twofold. First, system costs are constrained. While some programs do obtain additional funding when needed, such funding is often at the expense of other programs or future modernization. Second, understanding “trade space” is the foundation for smart decision making. Trade space is the range of alternatives available to decision makers. It is four-dimensional; comprising performance, cost (i.e., TOC), schedule, and risk impacts (Kaye

et al., 2000:354). The trade-off process is more effective if it can be accomplished earlier in the acquisition life-cycle of a system. A large percentage of cost is determined by a small percentage of the decisions. These critical, cost-driving design decisions are made early in the concept selection and design process (Rush, 1997:165).

According to Kaye et al., “Clear identification and use of viable trade space, or the range of alternatives, with full knowledge of real and potential impacts is essential for making the right decisions to meet user needs while controlling cost” (Kaye et al., 2000:355). Trade space is commonly defined for alternatives in terms of performance, cost, and schedule impacts that each alternative presents (Kaye et al., 2000:355). Risk must also be addressed. Risk drives many critical decisions and is a fourth dimension in the trade space. Additionally, risk “discounts” the anticipated performance, cost, and schedule options; it restricts trade space (Kaye et al., 2000:355).

Figure 4 depicts the cost-performance trade space of a KPP for a notional weapon system. The KPP is characterized by threshold and objective levels, found on the performance-axis. The KPP’s cost is bounded within a predetermined life-cycle cost target. The shaded region includes all feasible solutions. The “solution set” line equates the optimum cost-performance combinations. Feasible solutions not found on the solution set line are sub-optimal, meaning more performance for equal cost or equal performance at less cost is possible (Kaye et al., 2000: 356). The “risk reserve” line constrains the trade space and limits the region of feasible solutions. Trade spaces, like the one depicted in Figure 4, exist for all system performance parameters (both key and non-key).

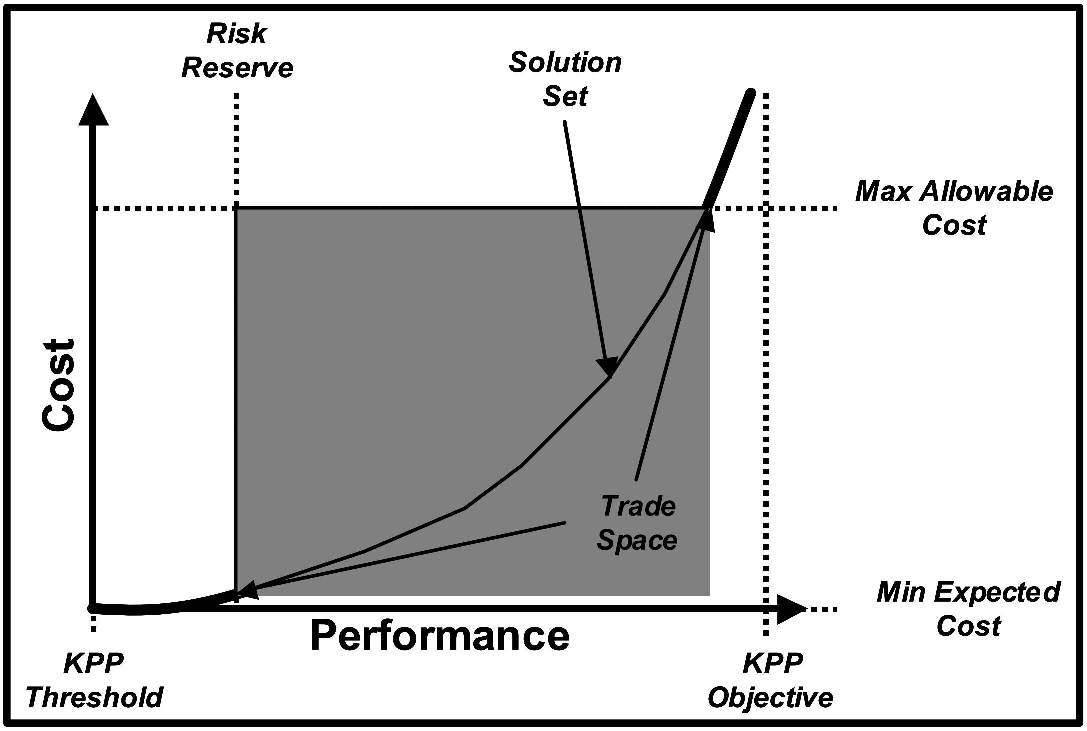

Figure 4. Cost / Performance Trade Space (Kaye et al., 2000)

While trade-offs are central to CAIV implementation, risk management is integral as well (Kaye et al., 2000:361). Risk management's role recognizes that a program cannot afford to avoid all risk, but rather must manage critical risks (Kaye et al., 2000:356). Because risk influences the available trade space, risk reduction measures must be addressed when performing cost-performance trade-offs.

Identification of the trade space is followed by rigorous and formal cost/benefit trade-off analyses; beginning at initial concept development and continuing into production and sustainment. One of the primary goals of this analysis is to identify the "knee of the curve" after which each marginal increase in capability or performance becomes increasingly expensive (Lorell and Graser, 2001:34). This analysis is necessary so that the user understands the cost of increasing performance in any given area and recognizes at what point the phenomenon of diminishing marginal returns comes into

play. Thus, the user community can make informed judgments regarding the priority of performance requirements and the allocation of resources (Lorell and Graser, 2001: 36).

CAIV implementation relies upon the use of capability-based requirements (Kaye et al., 2000:357). Instead of specifying how to build a system and how to allocate subsystems, the user must instead state what the system needs to bring to the fight. This approach to system definition increases flexibility and further aids the development team in delivering the "best-value" system that meets user operational requirements (Kaye et al., 2000:356). The user must then carefully prioritize the mission performance needs and capability-based requirements. Prioritization is critical to facilitate intelligent trade-offs between cost and capability. A key objective of prioritization is to avoid "over designing" or "gold-plating" weapon systems with higher performance and more extensive capabilities that are not truly necessary to perform the mission (Lorell and Graser, 2001:34). Thus, prioritization helps to exclude nonessential requirements while helping the development team maximize use of the trade space by focusing on characteristics contributing most to mission accomplishment (Kaye et al., 2000:356).

Beyond simple prioritization, it is essential to understand the explicit and implicit relations between the individual capabilities-based requirements (or performance parameters) (Wollover, 1997:317). A means is required to systematically organize all of these variables and their interrelationship (Wollover, 1997:317). Quality function deployment (QFD) is a well-established procedure used to organize and translate user requirements. QFD has been used extensively, across many industrial sectors, to translate and map user needs into objective system outcomes (Wollover, 1997: 318). The literature indicates that QFD is the most widespread implementation methodology for

total quality management (TQM) (Sage, 1992: 222). QFD is a process tool that enhances a development team's ability to manage key elements of the system engineering process (Wollover, 1997: 318).

Through a series of interdependent matrices, QFD accommodates vaguely stated customer specifications. These matrices allocate and map requirements into specific design strategies, development processes, and system characteristics (Wollover, 1997: 318). For each element of the system design, technical performance measures (TPMs) are addressed and threshold/objective values assigned. Using an iterative process, these assignments set the minimum levels of achievement required to satisfy the user's overall requirements.

The literature reveals that QFD was developed in the late 1960s by Shigeru Mizano of the Tokyo Institute of Technology (Menon et al., 1994: 94). Around this time, Mitsubishi Heavy industries began to use QFD on supertanker projects. These projects were characterized by having sophisticated propulsion, maneuvering, and balance control, challenging design and manufacturing logistical requirements (Guinta et al., 1993: 1). Toyota then adopted the Kobe shipyard QFD strategy, modified its methodology, and experienced 40 percent reductions in new model development costs and 50 percent reductions in development time (Menon et al., 1994: 94). U.S. firms such as Ford, Ernst and Young, Texas Instruments, General Motors, ITT, and IBM have also embraced QFD strategies. Research reveals that various domestic manufacturing companies using QFD have experienced 50 percent cost reductions and 33 percent project time reductions (Guinta et al., 1993: 8). The DoD Joint Strike Fighter (JSF)

program has adopted QFD techniques and has been recognized for its aggressive implementation to better analyze weapons system requirements (Wollover, 1997:320).

The DoD's emphasis upon integrated product and process development (IPPD) and the integrated product team (IPT) structure enhances the applicability of QFD to CAIV implementation (Wollover, 1997: 320). Precedent dictates that cost/performance IPTs (CPIPTs) oversee the execution of CAIV initiatives within DoD programs. QFD provides the means to trace cost objectives as they are decomposed from the system to the sub-systems level. The CPIPT may then use the QFD products to recommend engineering and design changes to the program manager so that CAIV objectives are met (Wollover, 1997:320).

QFD assists CAIV implementation in several ways. Most directly, QFD comprehensively displays relationships between various cost variables (i.e., cost drivers). This aspect leads to more structured analyses and more intelligent prioritization schemes. The addition of technical performance measure (TPM) difficulty as a measure of risk further improves the quality of information available to assist in trade-off decisions. Finally, the multiattribute structure of the QFD matrix captures and interrelates the data necessary to design and evaluate multiattribute optimization problems (Wollover, 1997:330).

The topic of system design optimization through QFD is addressed by Thurston and Essington, Thurston and Locascio, and Fung et al.. Thurston and Essington explain how the weighted average method (i.e. prioritization) commonly used to optimize designs has limitations because it does not accurately reflect the nonlinear value imparted by performance parameters (Thurston and Essington, 1993:48). Instead, the authors employ

a utility theory-based model that incorporates user willingness to make trade-offs between performance parameters. Thurston and Locascio emphasize the importance of considering economic or non-technical factors when evaluating product designs (Thurston and Locascio, 1994:41). The authors demonstrate an analysis technique that allows designers to treat economic factors with the same respect they traditionally give to technical factors (Thurston and Locascio, 1994:41). Fung et al. integrate imprecision and uncertainty with a QFD-based multiattribute optimization problem formulation. The ultimate goal of the model proposed by Fung et al. is to help decision makers deploy design resources in a manner that improves overall customer satisfaction (Fung et al., 2002:585).

More directly related to CAIV, research by Luman presents an implementation process to support complex systems requirements allocation as a function of cost. Luman's research attempts to answer the question, "From the systems of systems performance perspective, where are the limited resources best applied" (Luman, 1999:8)? Through this process, Luman covers a broader category of CAIV implementation by addressing "systems of systems" issues. Systems of systems are generally viewed as having the following characteristics:

- The system is comprised by several independently acquired systems, each under a nominal systems engineering process;
- Time phasing between each systems system's development is arbitrary and not contractually related;
- System couplings are neither totally dependent nor independent, but rather interdependent;
- Individual systems are generally unifunctional when viewed from the system of systems perspective;

- Optimization of each system does not guarantee overall system of systems optimization; and
- Combined operation of the systems constitutes and represents satisfaction of an overall mission or objective (Luman, 1999:8).

From the "systems of system perspective," Luman's methodology presents two potential CAIV objectives. The first seeks to determine the optimal allocation of resources (developing new systems, modifying legacy systems, inserting advanced technology, or implementing a combination of these options) as a function of total cost. The second objective looks to optimize a specified top level measure of effectiveness (MOE) within the bounds of the stated constraints (Luman, 1999:8). It is possible to pare Luman's systems of system CAIV implementation methodology to address just this second objective in a narrower, discrete (non-system of systems) system context.

Figure 5 is a graphic representation of Luman's methodology. The process is characterized by two phases. Phase I involves developing closed form equations that relate system design components and parameters to system effectiveness. In this phase, a single overarching MOE for the system, characterizing mission success, is defined. This top-level MOE is related (via equations) to multiple measures of performance (MOPs). The MOPs correspond to system performance parameters (both key and non-key). Initial boundary conditions and constraints are then specified for the system MOPs (e.g., cost targets, technological bounds, force structure limitations, etc.). Performance based cost models (PBCMs) are developed to calculate cost as a function of the parameterized MOPs. Phase II then implements simulation techniques to solve the resulting constrained, nonlinear (stochastic) performance problem. Simulations are repeated,

gradually relaxing the overall cost constraint. Finally, sensitivity analysis is performed to understand the influence of the non-cost constraints (Luman, 1998:6).

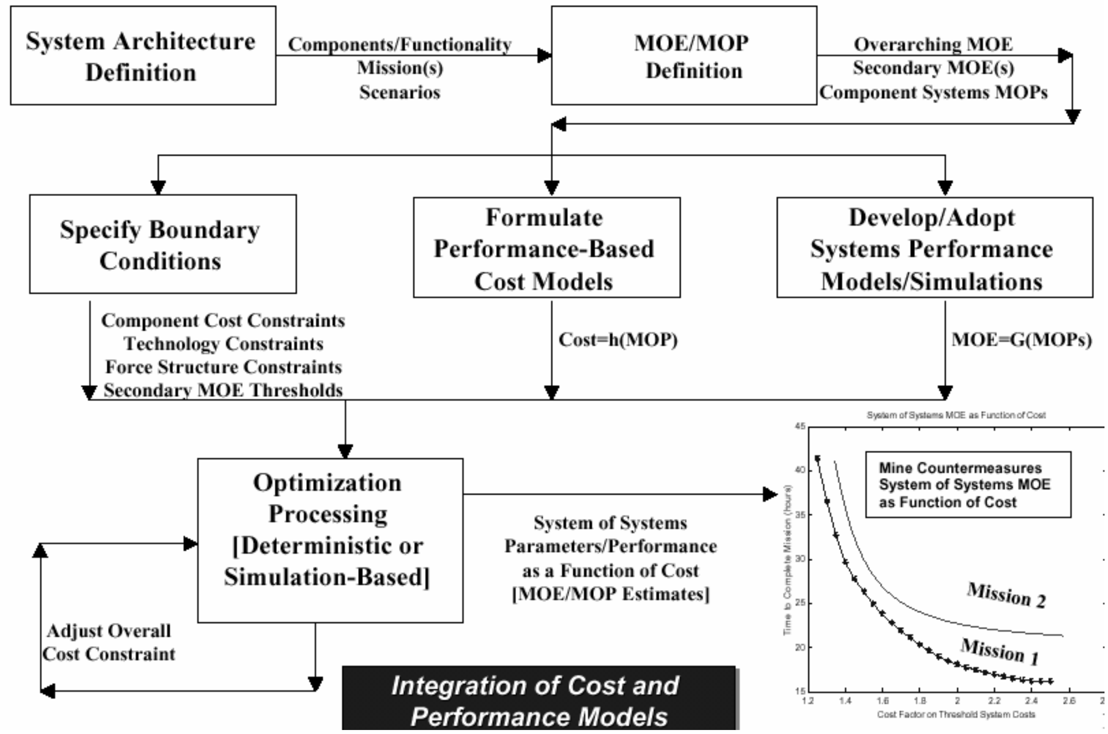

Figure 5. System of Systems CAIV Methodology (Luman, 1999)

Luman cites the following challenges to be wary of when implementing this CAIV methodology:

- Defining the overarching MOE,
- Allocation of system components and selection of trade space for MOPs,
- Adaptation/adoption of appropriate PBCMs,
- Application of efficient and appropriate optimization algorithms, and
- Verification and validation of process models (Luman, 1999:11)

While the methodology focuses on how best to upgrade complex systems of systems, the process can be reduced to find the "best" range of solutions for a particular system subject to cost, operational, and technological constraints, relative to an overarching measure of effectiveness.

Further work on CAIV implementation methodology has been conducted by the Systems Management and Production Laboratory (SMAPLAB), an applied research arm of the U.S. Army Aviation and Missile Command (AMCOM), NASA, and the University of Alabama. The SMAPLAB CAIV model is an electronic tool designed to support program management office (PMO) level IPTs trade-off analyses among cost, performance, and schedule elements. Utilizing a QFD-like approach, the SMAPLAB tool allows users to enter performance requirements and design characteristics, their correlations, and priority rankings. Using this data, the model outputs the critical relationships between pairs of performance requirements and design characteristic. The model also identifies performance requirements that are most sensitive to changes in design characteristics. Currently, the model does not integrate cost, performance, and schedule information. Additionally, the model does not provide values for the magnitude of trade-off impacts (Mullins, 1998:7-9).

Tecolote Research, Inc. has integrated a "first order" CAIV capability within the Automated Cost Estimating Integrated Tools (ACEIT) software suite (version 5.x). With this capability, one can set cost targets or time-phased budgets and obtain insight into how the driver within the cost estimating methodology is affected. An optimization algorithm generates a solution that satisfies the constraints specified for system cost and a single cost driver, or "free variable." The marketing literature for this tool states, "This

function is not meant to solve all of an organization's CAIV issues, but rather provide a means to gauge the impacts on cost estimating methodology drivers and provide direction for more thorough investigation" (Tecolote, 2002). Currently, the tool does not integrate requirements prioritization, an area of primary concern in CAIV analysis. Additionally, the solver algorithm employed by the tool is rather limited and does not allow the user to vary more than one decision variable. This limitation of the ACEIT approach thus hinders a holistic view when attempting to conduct CAIV trade-offs.

Utility Theory

Earlier, the topic of utility theory was mentioned when describing techniques for system design optimization with QFD. Because this concept plays a pivotal role in the formulation of the CAIV/EA model, it is important to present a brief survey of utility theory and its application to the overarching practice of decision analysis.

As described by Ragsdale (2001), the goal of decision analysis is to help individuals make good decisions. Although all decision problems are somewhat different, they share certain characteristics (Ragsdale, 2001:714). The following is a brief (non-exhaustive) list of the general characteristics of a decision problem:

- There exists at least two alternatives for addressing or solving the problem;
- An alternative is a course of action intended to solve the problem;
- Alternatives are evaluated on the basis of the value they add to one or more of the decision criteria; and
- The criteria represent various factors that are important to the decision maker (Ragsdale, 2001:714-15).

Often a decision maker is a faced with multiple criteria when evaluating a decision problem. Many times, these criteria compete or conflict with one another.

Utility theory presents one approach to assessing trade-offs between multiple criteria. Additionally, utility theory provides a means to incorporate a decision maker's attitude and preference toward risk and return in the decision analysis process so that the most desirable decision alternative is identified. Utility theory assumes that every decision maker uses a utility function that translates each of the possible alternatives in a decision problem into a non-monetary measure called utility. Utility represents the total worth, value, or desirability of the outcome of a decision alternative to the decision maker. Often utilities are represented on a scale from zero (0) to one (1), where 0 indicates that the outcome of the alternative has no value to the decision maker and 1 represents perfect or superior value (Ragsdale, 2001:757).

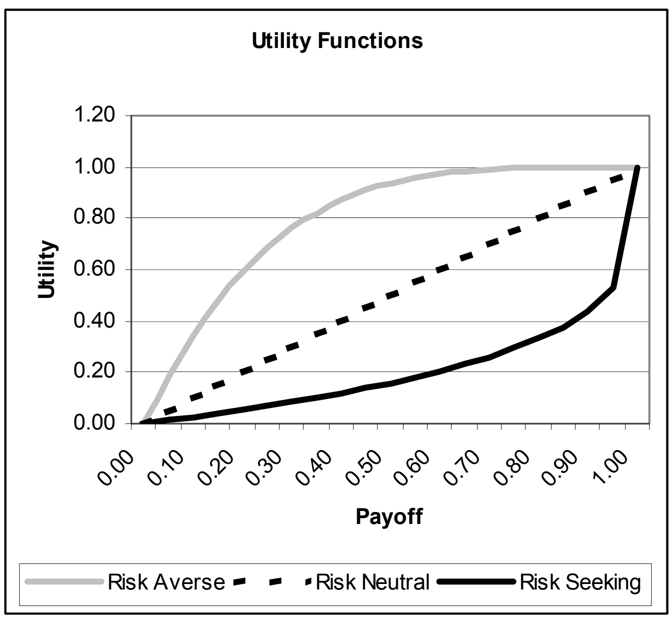

Figure 6. Utility Functions (Ragsdale, 2001)

Figure 6 illustrates three different decision maker attitudes toward risk. According to Ragsdale:

> "A 'risk averse' decision maker assigns the largest relative utility to any payoff but has a diminishing marginal utility for increased payoffs (that is, every

> additional increment of payoff results in smaller increases in utility. A 'risk seeking' decision maker assigns the smallest utility to any payoff but has an increasing marginal utility for increased payoffs (that is, every additional increment of payoff results in larger increase in utility. The 'risk neutral' decision maker falls in between these two extremes and has a constant marginal utility for increased payoffs (that is, every additional dollar in payoff results in the same amount of increase in utility)" (Ragsdale, 2001:757-58).

Applying utility functions to the criteria composing a multiattribute decision problem allows a decision maker to execute rigorous, quantitative trade-offs. When there are multiple, competing criteria, it is often challenging to reduce a decision to a single dimension. Fortunately, individual utility functions for the various decision criteria can be synthesized into an overall utility function that measures the decision maker's overall satisfaction for a given alternative. This approach to using utility theory to address multiattribute decision problems is fully developed in the next chapter.

III. Methodology

Overview

This chapter describes and substantiates the methodology used to integrate CAIV analysis within an EA strategy. First, the core CAIV model is formulated. Following this formulation, the model is expanded to incorporate the features of EA (e.g., time-phasing and technical risk mitigation). Finally, potential techniques for model validation are discussed.

Core CAIV Model Formulation

Based upon information presented in the previous chapter, the essence of CAIV implementation is embodied by disciplined cost-performance trade-off analysis (Rush 1997: 163). It is possible to model these trade-offs through the use of multiattribute design evaluation, incorporating economic factors as measures of performance. The challenge in performing this type of evaluation lies in developing an objective function that clearly and accurately integrates the various measures of performance associated with the design.

Luman uses an overarching system measure of effectiveness (MOE) that is mathematically linked to individual systems' measures of performance (MOP) as an objective function in his methodology (Luman, 1998:6). According to Thurston and Essington, "Recent efforts to include manufacturing cost considerations in the design process incorporate a step in which design alternatives are compared on the basis of their performance in several attributes. The most common method used in this type of

multiple attribute evaluation of a design is some form of weighted average" (Thurston and Essington, 1993:49).

The weighted average approach employs the following functional form:

$$T(x) = \sum_{i=1}^{n} w_i \cdot x_i \tag{1}$$

In this formulation, T(x) is the total worth of an alternative characterized by attribute vector x = (x_1, ... , x_n); x_i is the level of the performance attribute i; i equals the 1, 2, …, n attributes; and w_i is the weighting factor (Thurston and Essington, 1993:49).

According to Thurston and Essington, this approach has two limitations. First, it assumes a linear relationship between the level of an attribute x_i and its subsequent worth or value to the decision maker. There are many instances where this relationship is not linear, because decision makers do not attach the same value to each unit of benefit they receive or expense they pay (Thurston and Essington, 1993:49). Figure 7 illustrates a notional non-linear relationship between value and performance.

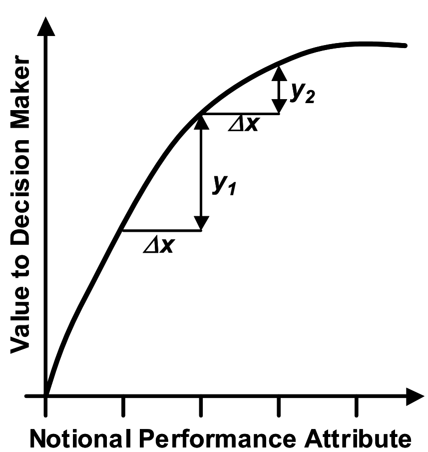

Figure 7. Notional Non-Linear Relationship (Thurston and Essington, 1993)

Second, the approach does not accurately capture the trade-offs decision makers are willing to make between attributes. This is the result of weighting factors being assigned values based upon an ad-hoc assessment of relative importance of one attribute to another rather than the decision maker's willingness to make trade-offs between attributes (Thurston and Essington, 1993:49).

For the reasons listed above, Thurston and Essington assert that utility analysis is superior to conventional weighted average methods for multiattribute design evaluation. In general, this approach disaggregates a complex and difficult decision-making problem into separate components. Next, the decision maker's statements of preference for each component are collected. Finally, the components are reassembled to provide overarching guidance (Thurston and Essington, 1993:50).

The general form of the multiplicative multiattribute utility analysis objective function is listed below:

$$U(x) = \frac{1}{K}\left[\left[\prod_{i=1}^{n}\left(K \cdot k_i \cdot U_i(x_i) + 1\right)\right] - 1\right] \qquad (2)$$

In this formulation, $U(x)$ is the overall utility of an alternative characterized by performance attribute vector $x = (x_1, \ldots, x_n)$; x_i is the level of the performance attribute i; $U_i(x_i)$ is the single performance attribute utility function for attribute i; i equals the $1,2,\ldots,n$ attributes; k_i is the single performance attribute scaling constant; and K is the normalizing constant (Thurston and Essington, 1993:50). Values for the single performance attribute utility functions range from zero to one. When all performance attributes are at their best, the overall utility equals one. Conversely, when all of the performance attributes are at their worst, the overall utility is set equal to zero.

Thurston and Essington emphasize the point that the scaling constants, k_i, are not arbitrarily assigned weighting factors, nor do they imply relative importance of attributes. Instead, k_i, imply the decision maker's willingness to make trade-offs between performance attributes (Thurston and Essington, 1993:50). The normalizing constant, K, is derived from the following:

$$1 + K = \prod_{i=1}^{n} \left(1 + K \cdot k_i\right) \tag{3}$$

The single performance attribute scaling constants, vector k, are derived from the overall utility function (Equation (2)) when performance attribute level x_i is at its best and all other attributes are at their worst. Ultimately, these scaling constants represent the user's willingness to improve in one performance attribute while incurring changes in competing attributes (Thurston and Locascio, 1994:50)

From a CAIV perspective, the performance attribute vector x = ($x_1, \ldots, x_n$) is analogous to the weapons system performance parameters specified in the ORD. Working in concert with the user, it is possible to develop single performance attribute utility functions for each of the performance parameters. These single attribute utility (SAU) functions are based upon the specified threshold and objective levels of performance for the parameters. Additionally, each SAU function represents the value the user places upon marginal improvements in performance for the respective parameter. Using the technique described by Thurston and Essington, it is possible to assign values to the scaling constants, vector k, by evaluating the overall utility function when performance parameter x_i is at its best and all other performance parameters are at their

worst. Having populated the scaling constant vector, it is then possible to determine the normalizing constant *K* through the use of Equation (3).

Preparing the overall utility objective function is an important step in formulating the CAIV analysis problem. However, as it stands, the formulation is incomplete. As might be inferred from the previous paragraph, the decision variables used in Equation (2) are defined in terms of performance. Consequently, this form limits the incorporation of economic considerations into the utility analysis. The primary reasoning for this limitation is that it is difficult to assess the cost of an alternative based solely on the levels of the performance parameters. Instead, it is necessary to associate the performance attributes with weapon system design attributes. Having developed the design attribute vector, $z = (z_1, \ldots, z_m)$; where z_j is the level of design attribute j; and m equals the 1, 2, … , m attributes; it is then possible to employ conventional cost estimating methodologies to determine the economic cost of an alternative.

Thurston and Locascio describe how the overall utility function can be modified to incorporate design attributes. By determining the relationship between the design attribute vector (z) that directly controls the performance attribute vector (x), one can then define the performance attribute function as the following:

$$x = g(z) \tag{4}$$

The definition of the performance attribute vector in terms of design attributes results in a modification to the overall utility function:

$$U(x) = U(g(z)) \tag{5}$$

Thus, the overall utility of an alternative is now defined by the levels of the design attribute vector (Thurston and Locascio, 1994:64).

Defining an alternative in terms of its design attributes offers several advantages when performing CAIV analysis. First, system developers make direct decisions on design attributes. Attained performance levels are a result of these design decisions. For example, a mechanical engineer employs a certain design geometry to meet a given strength (i.e., performance) requirement; not the other way around (Thurston and Locascio, 1994: 64). The second advantage lies in the opportunity to expand the trade space. While the number of performance attributes is fixed, the number of design attributes is theoretically infinite. The developer is limited only by his imagination and the realm of the possible when synthesizing the design attribute vector for Equation (4). The final advantage has already been cited. Current cost estimating models are calibrated to derive cost as a function of design attributes, not performance.

The remaining challenge in formulating the core CAIV model is generating the function specified by Equation (4). This function derives the performance attribute (PA) vector from the design attribute (DA) vector. As previously described, QFD presents a rigorous technique for tracing customer requirements (i.e., PA) to design alternatives (i.e., DA). Fung et al. describe the QFD matrix which expresses the relationship between PA and DA. The relationship matrix, with elements R_{ij}, indicates the strength of the relationship between the *i*th performance and the *j*th design attributes. R_{ij} is quantified on a specified scale (Fung et al., 2002:587). If increasing the level of z_j improves x_i, then a positive relationship exists. Conversely, if increasing the level of z_j degrades x_i, a negative relationship is present. On a -3 to 3 scale, a strong positive relationship between x_i and z_j is given a value of positive three. A strong negative relationship is denoted by negative three. A negligible relationship is indicated by no

entry in the matrix element (equals zero (0)). Table 2 depicts a notional QFD relationship matrix:

Table 2. Notional QFD Relationship Matrix

Performance Attribute	Design Attribute 1	2	3	4	5	6
1	-3	2		2	1	
2		3	3	1	1	1
3	2	-2	-2	3	3	-1
4			3		3	
5	2	3	2	1	-1	

Again, the system developer only controls the level of attainment for the design attributes, z_j. Therefore, the decision variable reduces to z_j. To proceed, it is necessary to normalize the DA level of attainment by comparing z_j to the maximum estimated level of attainment for that attribute, z_{jmax}. Any attainment beyond z_{jmax} is assumed to generate no value to the design. Thus, z_j is constrained by z_{jmax}. The ratio of z_j to z_{jmax} returns the normalized level of attainment for the design attribute, z_j^{θ}.

R_{ij} also requires normalization. Normalization is accomplished by dividing R_{ij} by the sum of the absolute values of the matrix elements for performance attribute i. This ratio produces the normalized relationship index, R_{ij}^{θ}. After normalizing both R_{ij} and z_j it is then possible to calculate the corresponding values for the normalized PA, x_i^{θ}. The following equation describes how the normalized PA is derived from the normalized DA and relationship index:

$$x_i^{\theta} = \sum_{j=1}^{m} R_{i,j}^{\theta} \cdot z_j^{\theta} \qquad (6)$$

After calculating the normalized level of attainment for a given PA, it is necessary to determine how the relative zero to one range translates to actual performance, x_i. The

system developer needs to develop a functional form that accomplishes this translation. Both linear and non-linear functions are possible. Additionally, the functions may be unique for each i. Equation (7) describes the translation function:

$$x_i = h_i\left(x_i^{\theta}\right) \tag{7}$$

Equations (6) and (7) only address calculating non-economic performance attributes. However, an underlying reason for using z_j as the decision variable is to facilitate calculating the cost of an alternative. Therefore, an equation is needed to translate the level of the design attribute, z_j, into a cost value.

$$C_j = c_j \cdot z_j \tag{8}$$

Equation (8) calculates C_j, the cost for design attribute j, by multiplying the design attribute level, z_j, by the cost factor vector, $c = (c_1, \ldots, c_j, \ldots, c_n)$, which is indexed to j. The cost factors, c_j, are derived from collaboration between system developers and cost estimators. The total cost for an alternative is calculated from the following:

$$TC = \sum_{j=1}^{m} C_j \tag{9}$$

As demonstrated by Equation (9), the total cost for an alternative, TC, is the sum of the costs for the m design attributes, C_j.

Upon deriving a means to determine the total cost for an alterative, it is vital for economic factors to be incorporated into the overall utility function described by Equation (2). As cited in previous chapters, guidance on CAIV dictates that total cost must be treated as a measure of performance. Thus, the overall utility of an alternative must reflect the user's value of an alternative's cost. The user must decide on the shape the SAU function specific to cost PA. Additionally, a scaling constant must be developed

for the cost performance attribute that indicates the user's willingness to make cost trade-offs. As a measure of performance, TC is calculated directly from z_j. Consequently, it is not necessary to formulate a normalizing translation function, like the one specified by Equation (7) for this performance attribute. Instead, TC is directly equivalent to x_i, where i is the index specific to the cost PA.

Having defined all of the variables necessary to formulate the core CAIV analysis model, it is vital to discuss the subject of constraints. The core model employs a cost target as the primary system constraint. Based upon this constraint, the model seeks to optimize the overall utility of the system by varying the levels of attainment for the individual design attributes. Additional side constraints for technical performance may also be considered. However, because the SAU functions are derived from the threshold and objective levels of performance specified by the ORD, there is the potential to over constrain the system by adding performance side constraints.

Using notation presented above, it is possible to formulate the core CAIV analysis model as a mathematical program seeking to optimize the overall utility of the weapon system (Thurston and Locascio, 1994:64):

$$\begin{array}{ll} \text{maximize:} & U(x) \\ \text{by varying:} & z \\ \text{subject to:} & x = g(z) \\ & TC \leq TC_{\max} \\ & z_{j\min} \leq z_j \leq z_{j\max} \end{array} \tag{10}$$

The program specified by Equation (10) uses the cost target, TC_{max}, as its primary constraint. TC_{max} is the threshold level for system cost. This level is based upon economic resources available to the system developer. The second constraint employed is the bounding of the design attribute level, z_j, between zero and the maximum level of

attainment, z_{jmax}. The reasoning for this constraint has been described above. One may then solve this program by using one of the many commercially available optimization applications.

Initial CAIV analysis begins by first determining the maximum cost required to attain x_{imax} for all performance attributes, i, except for total cost. The total alternative cost resulting from this solution equates to the cost ceiling, $TC_{ceiling}$. The total cost ceiling is interpreted as the level of funding beyond which no additional technical performance is gained. At this point, all non-economic PA are maximized. Next, by incrementally decreasing the cost target, TC_{max}, from the cost ceiling, $TC_{ceiling}$, and then solving the non-linear program specified in Equation (10) for each cost increment, it is possible to understand how overall utility behaves as a function of total cost. Figure 8 presents a notional depiction of this behavior.

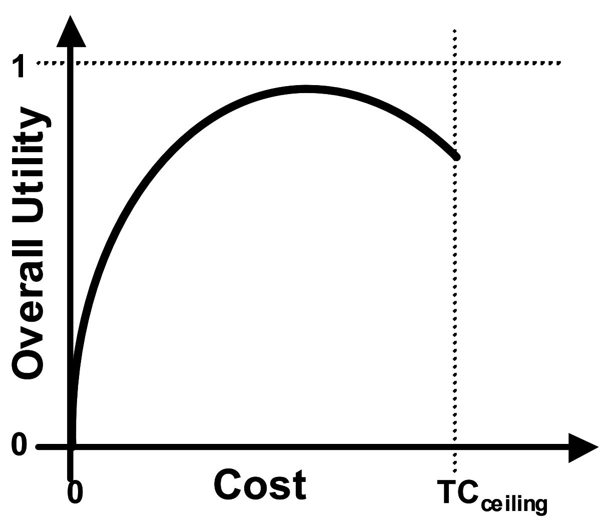

Figure 8. Notional Depiction of Overall Utility as a Function of Total Cost

Evaluating overall utility as a function of cost allows one to assess the marginal benefit (or detriment) incurred by incrementally increasing (or decreasing) the cost target

from its current level. Such analysis helps to identify the “knee of the curve;” the point at which each marginal increase in utility becomes increasingly expensive (Lorell and Graser, 2001:34). It is also possible to examine the individual solutions for each x_i and z_j. Such analysis reveals how the individual performance attributes behave and how the economic resources are distributed to each of the design attributes as the total cost constraint changes.

Expanded CAIV/EA Model

Having established the foundations for the core CAIV model, it is now possible to begin integrating features specific to EA. As it stands, the core CAIV model seeks to optimize the overall utility for a single system development activity. The core model is consistent with a “single step” acquisition strategy. Using a single step approach, the user gains benefits from the system (in terms of its technical performance and capabilities) only after the development activity is complete. The limitations associated with this approach have been explained previously. An EA approach seeks to overcome these limitations by incrementally delivering to the user solutions to operational requirements (i.e., capabilities, MOPs, etc.), over time. Along the way, an EA approach mitigates technical risk and uncertainty by delivering lower risk requirements in earlier increments and higher risk requirements in later ones (after the risk has been reduced by a combination of spiral development activities). Thus, the expanded CAIV/EA model needs to incorporate two additional features: time-phasing and technical risk mitigation.

Incremental delivery of capability and requirements phasing introduce an additional dimension into the model, time. EA increments are assumed to occur sequentially over time. While there may be some overlap between two increments,

general practice dictates that completion of one increment does not occur until the completion of the preceding increment (except for the first, or core increment, which has no predecessor). Thus, the expanded CAIV/EA model treats each increment as a discrete development activity.

The expanded model dimensionality is implemented through the addition of the subscript variable l, which augments some of the core model parameters. In many cases, this addition changes many variables, which were previously described as vectors, into matrices. For example, the performance attribute variable, x_{il}, represents the level of the ith performance attribute for the lth increment. The total design attribute variable, Z_{jl}, represents the total level of the jth design attribute for the lth increment. In all cases, the variable, l, equals the 1, 2, … , p increments.

With regards to the total design attribute variable, Z_{jl}, there is a reason for capitalizing the letter "z." Capitalization differentiates the total level of the design attribute from the incremental level of the design attribute, z_{jl}. The incremental design attribute variable, z_{jl}, represents the level of the jth design attribute for the lth increment. Because an EA strategy centers on increasing a systems capability over a series of increments, it is assumed that the latter increments build upon the work accomplished during earlier ones. Thus, z_{jl} represents the marginal increase in DA accomplished in a given increment. Whereas, Z_{jl} represents cumulative level of a design attribute for a given increment, taking into account the present increment's marginal increase as well as prior increments' levels of attainment. The Equation (11) describes the relationship between the total and incremental levels of DA attainment.

$$Z_{j,l} = Z_{j,l-1} + z_{j,l} \tag{11}$$

The previous discussion has begun to integrate EA time-phasing characteristics with the core CAIV model. However, before this feature can be fully addressed, it is essential to discuss the other aspect of EA, technical risk mitigation. As was described in previous chapters, EA embraces the concept that capabilities with lower technical risk should be delivered earlier in the development cycle than higher risk capabilities. Additionally, an EA approach (employing spiral development techniques) suggests that technical risk can be reduced over the course of the development cycle through an iterative process of systems engineering, experimentation, operational evaluation, and user feedback (see Figure 2). Thus, the degree of technical risk should reduce as the development cycle proceeds from earlier to later increments.

Risk is incorporated into the model with the matrix $D_{j,l}$, the degree of technical risk associated with jth design attribute for the lth increment. The technical risk parameter discounts the level of the incremental design attribute variable, z_{jl}, and thus affects the level of the total design attribute variable, Z_{jl}, as well. Values for $D_{j,l}$ range from zero (easily attained) to one (impossible to attain). The relationship between the technical risk variable and the design attribute variables is expressed by modifying Equation (11).

$$Z_{j,l} = Z_{j,l-1} + \left(1 - D_{j,l}\right) \cdot z_{j,l} \qquad (12)$$

The technical risk factor discounts the realized attainment for an incremental design attribute variable. Thus, the incremental design attribute variable can be considered a planned level of attainment, while the product of the incremental DA variable and the technical risk factor is equivalent to the actual level of attainment. This formulation

implies that higher risk activities realize inferior levels of DA attainment than lower risk activities.

As was cited previously, the EA approach assumes that technical risk decreases as the development cycle proceed from earlier to later increments. Therefore, the expanded CAIV/EA model must include the following assumption:

$$D_{j,l} \leq D_{j,l-1} \qquad (13)$$

Equation (13) indicates that the technical risk factor for an increment must be less than or equal to the technical risk factor for the preceding development increment, for a given design attribute. The values for the technical risk factors are derived from expert opinion and input from the various system development IPTs. The degree by which the technical risk factors reduce over time should be based upon the level and extent of risk mitigation activities being accomplished as part of the spiral development process. Again, this assessment needs to be made by those who are involved with the system development IPTs.

Having integrated technical risk mitigation into the expanded CAIV/EA model, it is now possible to finish integration of the time-phasing component. There are additional core parameters that are affected by the expansion of the time dimension. The elements of the cost factor matrix, $c_{j,l}$, represent the cost factors associated with jth design attribute for the lth increment. As a result of this change, the elements of the design attribute cost matrix, $C_{j,l}$, represent the cost of the jth design attribute for the lth increment. The rationale for variation in the cost factor term is based upon learning curve improvements and other efficiencies, which often result as the development cycle proceeds forward into time. The incremental total cost is expressed by the vector $tc = (tc_1, \ldots, tc_l, \ldots, tc_p)$, where

tc_l represents an alternative's total cost at the lth increment. Finally the overall total cost is calculated from the following:

$$TC = \sum_{l=1}^{p} tc_l \tag{14}$$

The overall total cost for an alternative, as calculated by Equation (14), sums the incremental total costs across the p increments.

For simplicity's sake, the expanded CAIV/EA model assumes that the scaling constants, k_i, remain the same from one increment to the next (at least for an initial iteration of the model). Along this line, it is also assumed that the single attribute utility functions do not vary from one increment to another. However, because of the recursive nature of EA, it is quite possible that the data for these two components will require updates as the development cycle proceeds. Upon completion of an actual development increment, it is likely that the user will have new guidance regarding their willingness to make trade-offs between performance attributes (hence the need to modify the scaling constants). Regardless of the situation, it is vital to keep the utility data current and in-line with user preferences. Finally, the elements of the performance/design attribute relationship matrix, R_{ij}, are assumed to remain constant from one increment to another.

There remain two more additions to the core CAIV model. First, the notation for the overall utility function must be modified to reflect the utility associated with a given increment.

$$U(x_l) = \frac{1}{K}\left[\left[\prod_{i=1}^{n}\left(K \cdot k_i \cdot U_i\left(x_{i,l}\right)+1\right)\right]-1\right] \tag{15}$$

Equation (15) calculates the incremental utility vector, $u = (u_1, \ldots, u_l \ldots, u_p)$, for the lth increment. There exists an incremental utility function for each of the p increments. The second and final modification is the creation of a new overall utility function. It is necessary to express the overall utility as a function of the individual utilities for each of the increments. Additionally, it is necessary to incorporate the user's preference for the character of the development cycle schedule. These schedule preferences are specified by the schedule weighting factors.

$$U(u) = \sum_{l=1}^{p} s_l \cdot u_l \qquad (16)$$

The overall utility, U, as calculated from Equation (16) is the sum of the incremental utilities, u_l, each multiplied by their respective schedule weighting factor, s_l. The values for the schedule weighting factors sum to unity. Therefore, the larger an increment's schedule weighting factor, the more emphasis is placed on increasing the utility for that increment. Because the increments are assumed to occur sequentially, the schedule weighting factors dictate the nature of the development cycle (i.e., the factors suggest the increment, and thus the point in time, where the preponderance of weapon system capability is delivered).

Based upon the changes described above, it is now possible to formulate the expanded CAIV/EA model as a non-linear program.

$$\begin{array}{ll} \text{maximize:} & U(u) \\ \text{by varying:} & z \\ \text{subject to:} & u = u(x_l) \\ & x_l = g(z_l) \\ & TC \leq TC_{max} \\ & Z_{jmin} \leq Z_j \leq Z_{jmax} \end{array} \qquad (17)$$

While the program described by Equation (17) closely resembles the one used in the core CAIV model, there are two important differences. First, the objective function has been modified to optimize the overall utility for each of the *p* development increments. Second, the decision variable, z_{jl}, represents the planned marginal increase in the level of attainment for the design attribute. This is a significant difference from Equation (10), where the decision variable was the realized level of attainment for a design attribute. These two differences relate directly back to the two underlying themes of EA, time-phasing and technical risk mitigation. The remainder of the expanded CAIV/EA model is consistent with the one described in the previous section. The total cost for an alternative, *TC*, is bounded by the cost target, TC_{max}. Finally, the cumulative level of (realized) attainment for a design attribute, Z_{jl}, is bounded by zero and the maximum level of attainment for that attribute, Z_{jmax}.

The analytical approach described for the core model remains valid for the expanded CAIV/EA model. By first identifying the cost ceiling, and then incrementally reducing the cost target, TC_{max}, from the ceiling, it is possible to understand how the overall utility (as well as incremental utility) behaves as a function of cost.

Model Evaluation Techniques

Having formulated the CAIV/EA model, it is important to determine whether or not it accurately reflects the integration of CAIV analysis within an EA framework. According to Law and Kelton, one of the most difficult problems in modeling is trying to determine whether a model is an accurate representation of the actual system being studied, i.e., whether the model is valid (Law and Kelton, 2000:264). Validation is the

process of determining whether a model is an accurate representation of the system, for the particular objectives of the study (Law and Kelton, 2000:265).

Law and Kelton assert that the most definitive test of a model's validity is to establish that its output data closely resemble the output data that would be expected from the actual system (Law and Kelton, 2000:279). Unfortunately, there are several facets that make validation of the CAIV/EA model, in this way, a challenging proposition. The CAIV/EA model is intended to serve primarily as a planning tool for weapon system development. Thus, by definition, the system which is being modeled is nonexistent. Consequently, it is not possible to compare the outputs from the CAIV/EA model to those from an actual development program. Additionally, the recent guidance from USD(AT&L) on the subject of CAIV/EA planning means there are presently no documented models available which might serve as benchmarks for comparison. Faced with these obstacles, how might one attempt to validate the CAIV/EA model?

Law and Kelton offer some suggestions when approaching validation of a model for a nonexistent system. They suggest a form of "concurrent validation" where validation takes place in concert with the development of the model. This concurrent validation relies upon a combination of management involvement, subject matter expert (SME) opinion, and sensitivity analysis (Law and Kelton, 2000:274-8). Fortunately, all of these components are available to assist in validating the CAIV/EA model.

Validation of the CAIV/EA model will occur via case study and will employ a "concurrent validation" approach. The notional ground based C2 system, will serve as a test case for this study. The test case system is analogous to a real-world Air Force development program, currently at an early point in its development cycle. The program

office managing the analog system is concerned about delivering the user an optimal level of performance while balancing budgetary constraints; thus making it a good candidate for CAIV analysis. Additionally, the analogous system is a complicated, software-intensive command and control system. As explained by the previous chapter, these characteristics suggest employing an EA strategy. In light of the USD(AT&L) guidance on CAIV/EA planning, the very nature of the test case system makes it a suitable test case for evaluation of the CAIV/EA model.

CAIV/EA model validation will begin with close interaction with the Air Force program management office. This interaction will help to provide a better understanding of the system, its architecture, and other characteristics important to the CAIV/EA model. Then, working with technical experts and cost estimators, the specific data required by the CAIV/EA model will be collected. Care will be taken to ensure that the data accurately reflects the nature of the test case system, as it is understood by those who have the greatest knowledge of it. Next, the model will be exercised and the output data will be collected. Appropriate analysis will be performed to glean specific information from the data (such as the behavior of overall and incremental utility as a function cost, performance attribute levels as a function of cost, etc.). Additional sensitivity analysis will be performed to help determine which model inputs and parameter have a significant impact upon the model outputs. This sensitivity analysis will help to determine which model inputs need to be modeled more carefully (Law and Kelton, 2000:278).

Luman also suggest of a series of challenges to be wary of when implementing a CAIV model. While his suggestions were specific to the "System of Systems" CAIV

model, they are also pertinent to the CAIV/EA model. To reiterate, Luman cited the following as being important to the CAIV model validation process:

- Defining the overarching MOE,
- Allocation of system components and selection of trade space for MOPs,
- Adaptation/adoption of appropriate performance based cost models, and
- Application of efficient and appropriate optimization algorithms (Luman, 1999:11).

In the context of the test case, the CAIV/EA model validation process will address each of these points to increase the validity of the model.

IV. Results and Analysis

Overview

This chapter begins with a description of the notional C2 system test case. Next, the particulars of the test case are integrated with the CAIV/EA model developed in the previous chapter. Several ground rules and assumptions are established to frame and assist the ensuing analysis. Next, the model is exercised, output data is collected, and preliminary analysis is performed. Based upon this initial analysis, several questions pertaining to the behavior of the model are raised. Finally, additional sensitivity analysis is accomplished to better describe how the CAIV/EA model responds to variations in its input parameters.

Test Case Description and Model Integration

As was mentioned in the previous chapter, a notional ground based C2 system, serves as a test case for this study. The notional system is intended to support air and space battle management and execution functions including data link management, surveillance, identification, and air battle execution for North American aerospace defense. The system is to provide surveillance and control of US airspace (including counter drug detection and monitoring operations), warning and assessment of aerospace attack, and response against air attack. The system shall also monitor airborne activity in support of North American Aerospace Defense's (NORAD) homeland defense (HLD), air sovereignty, and aerospace defense missions within its Area of Responsibility (AOR) on a continuous, uninterrupted basis. Additionally, the system is to provide effective and integrated battle management of aerospace defense resources during peacetime,

transition, attack, and post-attack periods. The system shall process, integrate, display, and distribute data from sensors, data links, and other C2 agencies to maintain situational awareness and support air interdiction operations.

Based upon this description of the notional C2 system, the following technical (i.e., non-economic) measures of performance are derived and listed below:

Table 3. C2 System Technical Measures of Performance

System Administration	Human-Machine Interface
Aerospace Surveillance	Target Identification
Weapons and Battle Management*	Tactical Data Links*
Training and Simulation	System Load Capacity

The addition of the economic measure of performance to this list (i.e., system cost) increases the total number of MOPs to nine (9). Thus, in terms of the notation presented in the previous chapter, there are nine (9) elements of the performance attribute vector x (n = 9). The ensuing table presents the relevant data associated with the performance attribute vector:

Table 4. C2 System Performance Attribute Vector Details

i	Name	Short Name	Units	Value Range
1	System Administration	Sys Admin	% Implemented	0:1
2	Human-Machine Interface	HMI	% Implemented	0:1
3	Aerospace Surveillance	Surveillance	% Implemented	0:1
4	Target Identification	Identification	% Implemented	0:1
5	Weapons and Battle Management	W & BM	% Implemented	0:1
6	Tactical Data Links	Data Links	% Implemented	0:1
7	Training and Simulation	Trng/Sim	% Implemented	0:1
8	System Load Capacity	Sys Load	% Implemented	0:1
9	System Cost	Cum Cost	$	0:Cost Ceiling

Table 4 explains each element (i) of the performance attribute vector x. Each element is described by its full name, a shortened name (for identification purposes during analysis), its unit of measurement, and finally by its range of valid values. For example, System Administration (or Sys Admin) is associated with element one (x_1) of

the performance attribute vector. The MOP is measured in terms of its relative degree of implementation. Based upon this designation, valid values for x_1 lie between zero (0) and (1). From this definition, it is inferred that zero percent implementation means that the MOP (and its associated capability) has not been implemented or addressed at all. Conversely, 100 percent implementation means that the MOP has been fully and completely implemented.

The CAIV/EA model does not require all values for the performance attribute matrix to lie within this range. In fact, the valid range for x_9 (System Cost) is between zero (0) and presumably some number much greater than one (1). Because elements $x_1 \ldots x_8$ are primarily descriptive in nature (as opposed to being measured and quantified) the decision to use a relative scale was based on the difficulty associated with establishing a relevant metric for each. Additionally, it is convenient to translate the normalized level of performance (x_i^θ) calculated from Equation 6 into the actual level of performance by selecting a translation function ($h_i\left(x_i^\theta\right)$) that returns a value of x_1 between 0 and 1. A more complete explanation of the translation functions used in this analysis follows shortly.

For the purposes of this analysis, it is assumed that the EA strategy specified for the notional C2 system is to be accomplished over the course of three increments (p = 3). In accordance with the guidance on EA described in Chapter II, each of these increments is intended to represent approximately 18 months in time. Additionally, the increments are arranged serially, in ascending order.

Table 5 specifies some additional data relevant to each of the MOPs. The table presents the performance function parameter (PFP), utility function parameter (UFP), and scaling constant for each *i*.

Table 5. Baseline MOP Model Parameter Specification

		MOP Factors		
MOP	Name:	PFP	UFP	ki
1	Sys Admin	1.00	1.00	0.10
2	HMI	1.00	1.00	0.10
3	Surveillance	1.00	1.00	0.10
4	Identification	1.00	1.00	0.10
5	W & BM	1.00	1.00	0.10
6	Data Links	1.00	1.00	0.10
7	Trng/Sim	1.00	1.00	0.10
8	Sys Load	1.00	1.00	0.10
9	Cum Cost	NA	1.00	0.10

The performance function parameter describes the shape of the translation function which converts the normalized level of performance (x_i^θ) into the corresponding performance attribute vector element. The performance translation function used in this analysis derived from an approximation to the cumulative distribution function (CDF) for the standard Beta distribution when $\alpha = 1$ (using the MS Excel Betadist function). The PFP controls the β parameter used in the Beta distribution.

Figure 9 illustrates the effect of PFP selection upon the translation from relative to absolute performance. This function behaves similarly to the utility functions described in Figure 6 of Chapter II. In fact, the utility function parameter (UFP) is used in the same manner as the PFP. The UFP also equates to the β parameter used in the standard Beta($\alpha = 1$) distribution (however, each MOP can have different values for their respective PFP and UFP). Finally, k_i is the single performance attribute scaling constant for MOP *i*. As

was described in the previous chapter, k_i represents the decision maker's willingness to make trade-offs with the specified MOP.

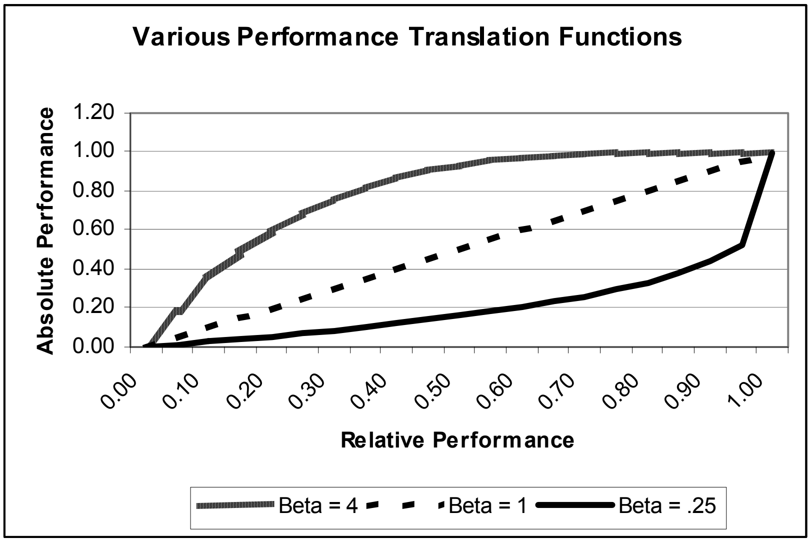

Figure 9. The Effect of PFP Selection upon Performance Translation

At the start of this analysis, all UFP and PFP values have been set to one (1). Additionally, all of the scaling constants have been set to 0.10. The resulting overall utility scaling constant (K) equals 0.261 (via Equation 2). This configuration of parameters indicates that there is a positive linear relationship between relative and absolute performance. There is also a positive linear relationship between absolute performance and single attribute utility (for technical MOPs). Because a decision maker would most likely have less value for more expensive alternatives, the single attribute utility function for the economic MOP is adjusted (by one (1) minus the resulting utility) to create a negative linear relationship between system cost and single attribute utility. Additionally, with all of the single performance attribute scaling constants set equal to each other, there is equal willingness to trade-off the MOPs when calculating overall utility via Equation 2. The elements of the schedule weighting vector, s, are also given equivalent weights (approximately 0.333) to add further parity.

As it stands, the model configuration expressed in Table 5 would most likely not be consistent with a decision maker's true value system and trade-off preferences. However, this implementation provides a baseline which can be exercised, evaluated, and then calibrated to better reflect the decision maker's preferences.

Table 6. Test Case System Design Attributes

j	Reqt #	Z_{jmax}	Units
1	4.1.1.1	2800	SLOC
2	4.1.1.2	2800	SLOC
3	4.1.1.3	700	SLOC
4	4.1.1.4	700	SLOC
5	4.1.3.1	2700	SLOC
6	4.1.3.2	2700	SLOC
7	4.1.3.3	2700	SLOC
8	4.1.3.4	2700	SLOC
9	4.1.3.5	720	SLOC
10	4.1.3.6	540	SLOC
11	4.1.3.7	540	SLOC
12	4.1.3.8	540	SLOC
13	4.1.3.9	540	SLOC
14	4.1.3.10	540	SLOC
15	4.1.3.11	540	SLOC
16	4.1.3.12	540	SLOC

The previous section looked only at the performance attributes of the test case system. Now it is time to consider the notional C2 system's design attributes; those elements that the decision maker controls and affects (i.e., the decision variables). Because the notional C2 system is software intensive, the system's functional requirements are treated as the decision variables for the CAIV/EA model. Table 6 presents the sixteen (16) design attributes (m = 16) considered in this evaluation. Table 6 also presents each design attribute's reference number (the citation that would identify the functional requirement in the system's technical requirements document (TRD)). The

column entitled "Z_{jmax}" describes the maximum level of attainment required to fully implement the corresponding design attribute. The final column describes the unit of measure for each design attribute. As has already been mentioned, the decision variables for this analysis are the various functional requirements implemented through software coding. Thus the appropriate units for all of the attributes are source lines of code (SLOC).

Table 7. C2 System QFD Matrix

			Performance Attributes (MOP) / i								
			1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	
Design Attributes			29	44	41	32	36	42	25	56	:Col Sum
j	TRD Req#	SLOC	Sys Admin	HMI	Surveillance	Identification	W & BM	Data Links	Trng / Sim	Sys Load	Row Sum:
1	4.1.1.1	2800	1	0	3	3	1	3	1	1	13
2	4.1.1.2	2800	0	3	3	3	9	3	0	3	24
3	4.1.1.3	700	1	1	1	3	1	3	0	3	13
4	4.1.1.4	700	0	0	3	1	3	1	1	9	18
5	4.1.3.1	2700	1	3	1	1	3	9	1	3	22
6	4.1.3.2	2700	1	1	9	1	1	1	0	3	17
7	4.1.3.3	2700	3	3	3	1	1	3	1	1	16
8	4.1.3.4	2700	3	1	3	1	1	3	0	9	21
9	4.1.3.5	720	1	9	1	1	3	3	1	1	20
10	4.1.3.6	540	3	1	1	3	3	3	0	3	17
11	4.1.3.7	540	0	3	3	1	0	1	1	3	12
12	4.1.3.8	540	1	1	0	1	3	1	3	3	13
13	4.1.3.9	540	3	3	3	1	3	3	1	9	26
14	4.1.3.10	540	1	3	3	9	3	3	9	1	32
15	4.1.3.11	540	9	9	3	1	0	1	3	3	29
16	4.1.3.12	540	1	3	1	1	1	1	3	1	12

Having described both the performance and design attributes, it is now possible to relate the two via a QFD matrix. Table 7 presents the matrix created by placing the performance and design attribute vectors orthogonal to one another. The resulting matrix is dimensioned by the number of technical MOPs and the number of design attributes

(8×16) (for formatting purposes, the matrix shown above has been turned 90-degrees to place the design attributes on the vertical axis). The elements of matrix R have been populated using a relationship scale ranging from zero (0) to nine (9). These elements represent the strength of the relationship between each pair of performance and design attributes. A value of zero (0) indicates no relationship exists between the performance/design attribute pair. A value of one (1) indicates "some" positive relationship exists. A value of three (3) represents a "strong" relationship, three times stronger than a value of one. A nine (9) is indicative of a "very strong" relationship, three times stronger than a value of three. While the values for the performance attribute model parameters will be adjusted over the course of the analysis, the values found in Table 7 will remain constant.

Table 8. C2 System Risk Matrix

j	Reqt #	Inc 1 Risk	Inc 2 Risk	Inc 3 Risk
1	4.1.1.1	0.13	0.01	0.01
2	4.1.1.2	0.31	0.06	0.03
3	4.1.1.3	0.13	0.05	0.00
4	4.1.1.4	0.33	0.28	0.24
5	4.1.3.1	0.38	0.32	0.03
6	4.1.3.2	0.26	0.05	0.02
7	4.1.3.3	0.08	0.05	0.02
8	4.1.3.4	0.24	0.00	0.00
9	4.1.3.5	0.02	0.00	0.00
10	4.1.3.6	0.12	0.10	0.03
11	4.1.3.7	0.05	0.05	0.01
12	4.1.3.8	0.24	0.05	0.02
13	4.1.3.9	0.33	0.31	0.06
14	4.1.3.10	0.24	0.05	0.01
15	4.1.3.11	0.37	0.05	0.02
16	4.1.3.12	0.13	0.00	0.00

Establishing the QFD matrix enables one to translate a system alternative's performance from its design. However, it is also necessary to be able to calculate the

realized level of attainment from the planned level of attainment for a given design attribute. Thus, to implement Equation 12 it is necessary to create the risk matrix *D*. Table 8 presents the 16×3 matrix generated by meshing the design attributes with the three development increments. The values for each of the elements in the risk matrix have the potential to range zero (0) to one (1). However, in this test case all of the risk has been assessed to be below 0.4. Examination of the matrix also reveals that as the development progresses from earlier toward later increments, the risk associated with any given design attribute decreases. This is consistent with the assumption made in the previous chapter that risk will decrease over time (due to technology maturation and risk mitigation efforts). Just as with the QFD matrix in Table 7, the values of the elements of the risk matrix in Table 8 will remain constant over the course of the ensuing analysis.

Analysis Ground Rules and Assumptions

Beyond the data cited in the previous section, some additional clarification is required to facilitate the upcoming analysis. The following is a list of the major analytical ground rules and assumptions:

- Although SLOC are technically discrete quantities, the values for the elements of the incremental design attribute vectors are considered continuous across their respective feasible ranges. The values for each Z_{jmax} are sufficiently large. Thus, there is little value in mandating integer values for each element of the incremental design attribute vectors.

- The software cost factor is \$89.52 per SLOC.

- The only costs considered by the model are those associated with the design attributes. While there would undoubtedly be additional costs associated with the development program (e.g., Systems Engineering / Program Management, Test, Data, etc.), this analysis only considers the direct costs associated with the design alternative.

- For all MOPs and their corresponding single performance attribute utility functions, the absence of performance attainment translates to a utility value of zero (0). Likewise, the objective level of the performance attribute translates to a utility value of one (1).

- To simplify the analysis, the threshold and objective levels for each measure of performance in each increment are held constant and equivalent. For technical MOPs, the threshold level occurs at 0% implementation and the objective level occurs at 100% implementation. For the economic MOP, the objective level corresponds to a system cost of $0.00 while the threshold level exists as the maximum design cost.

Initial Analysis

Using the data presented in the previous section, the notional C2 system test case has been implemented in a spreadsheet environment. A description of the spreadsheet model is available in the appendices. Below the surface of the model, the spreadsheet has been enhanced with Visual Basic for Applications (VBA) scripting to assist in automating the analysis. Some segments of VBA code are also found in the appendices. Finally, the Solver Excel add-in (by Frontline Systems, Inc.) has been used to solve the mathematical program specified by Equation 17 (implemented through the spreadsheet).

Based upon the initial parameter settings cited in Table 5, the resulting decision maker satisfaction (overall utility) is calculated and presented in Figure 10. The range on the horizontal axis spans from a design cost of $0.00 to the design cost ceiling of approximately $2,620,000. The design ceiling is calculated by determining the cost of meeting the objective level for each of the technical measures of performance, all within the first increment. Because the risk factor are the highest in the first increment, the resulting cost is much greater than if the development was allowed to progress and take advantage of the lower risk found in the latter increments.

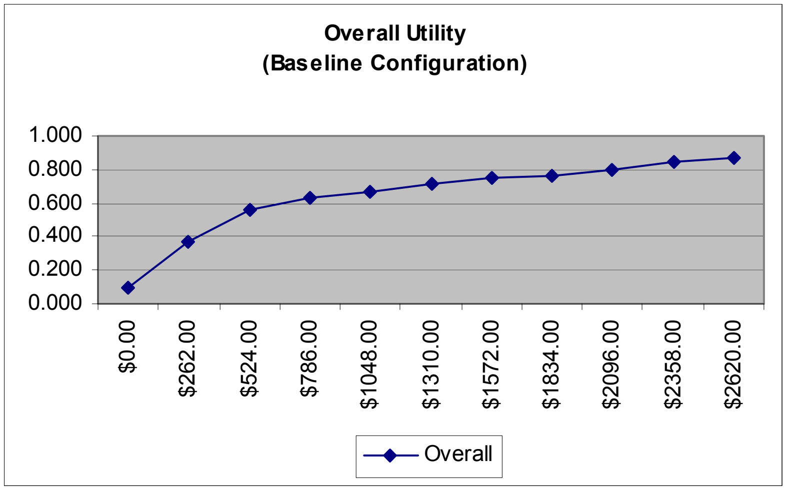

Figure 10. Overall Utility – Baseline Configuration (Table 5).

As Figure 10 indicates, at the far left of the cost range ($0.00), the overall utility is approximately 0.10. This value corresponds to the scaling factor selected for the economic MOP. In Chapter III it was stated that the scaling factors equate to the overall utility for the system when a given MOP is at its best level and all others are at their worse. Thus, when no money is spent on developing the system, there is no attainment for the technical MOPs and their resulting single attribute utility is zero (0). Conversely, when no money is spent, the economic MOP is at its best possible level and its resulting single attribute utility is one (1). When these values are fed into Equation 15, an overall utility equivalent to the scaling factor for system cost is generated (0.10).

Looking to the far right of the cost range, a similar phenomenon occurs. At the cost ceiling, all of the technical MOPs are at their objective levels of attainment. Thus, their resulting utilities are equal to one (1). However, the opposite holds for the economic MOP. At the cost ceiling, system cost is at its threshold level and equals zero (0). The resulting overall utility is approximately 0.88. From a heuristic standpoint, one would reason that with eight of nine MOPs at their highest utility and the remaining one at its worst (given that the decision maker is equally willing to trade-off each of the

MOPs), the resulting overall utility would be approximately 8/9 or 0.889. Thus the model appears to be consistent with the heuristic.

Based upon this analysis of the end points of the cost range it can be inferred from CAIV/EA model that the overall utility for a system will never be less than the value of the single attribute scaling factor for the economic MOP. Additionally, it will never be possible to have an overall utility equal to one (1). This observation is attributed to the relationship between the technical MOPs and the economic MOP. As the value of the technical MOPs increases, the value of the economic MOP decreases, and vice versa. Thus the trade space for overall utility exists between value for the economic MOP and some value less than one (1).

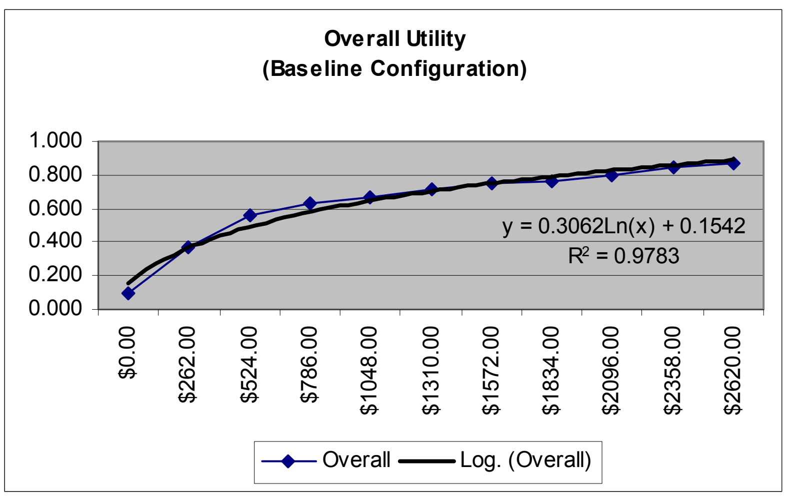

Figure 11. Baseline Configuration (Table 5) Regression Model.

As the system cost increases the overall utility for the system appears to increase as well. Figure 11 presents a modification to the chart presented in Figure 10. A regression line has been added to model the relationship between overall utility and cost. The regression line uses the natural logarithm of cost to produce an overall R-squared value of 0.9783.

The baseline configuration does not warrant any additional analysis. While it is possible to examine the how the technical MOPs behave over the system cost range, there is little value to that data. The trade-offs made in the baseline configuration are a function of the two parameters mentioned earlier: the values of the elements QFD matrix, R, and the levels of Z_{jmax} for each of the design attributes. A decision maker is more likely to be interested in how their value functions (determined by the UFP) and their preferences for trade-offs (set by the SAU scaling constants, k_i) affect the model. Thus, the parameter configuration specified in Table 5 will be adjusted to reflect a decision maker's preferences.

Table 9 specifies a different parameter setting, reflecting possible decision maker preferences. As the table indicates, the decision maker has adjusted his tolerance for risk. Seven of the eight technical MOPs now reflect a utility function that is risk averse (UFP = 3.00). This setting indicates that the decision maker places a diminishing marginal return on increases in performance for these MOPs. The decision maker has a risk seeking attitude towards the remaining technical MOP (Sys Load). By setting the UFP equal to 0.50, the decision maker is indicating a propensity for increasing marginal returns for this MOP. Finally, the UFP for the cost of the system has been decreased to 0.75. Figure 12 graphically depicts the effects of these new parameter specifications on the shape of the corresponding utility functions.

Table 9. Decision Maker Preference Specifications for C2 System

		MOP Factors		
MOP	Name:	PFP	UFP	ki
1	Sys Admin	1.00	3.00	0.10
2	HMI	1.00	3.00	0.10
3	Surveillance	1.00	3.00	0.10
4	Identification	1.00	3.00	0.10
5	W & BM*	1.00	3.00	0.30
6	Data Links*	1.00	3.00	0.30
7	Trng/Sim	1.00	3.00	0.10
8	Sys Load	1.00	0.50	0.10
9	Cum Cost*	1.00	0.75	0.30

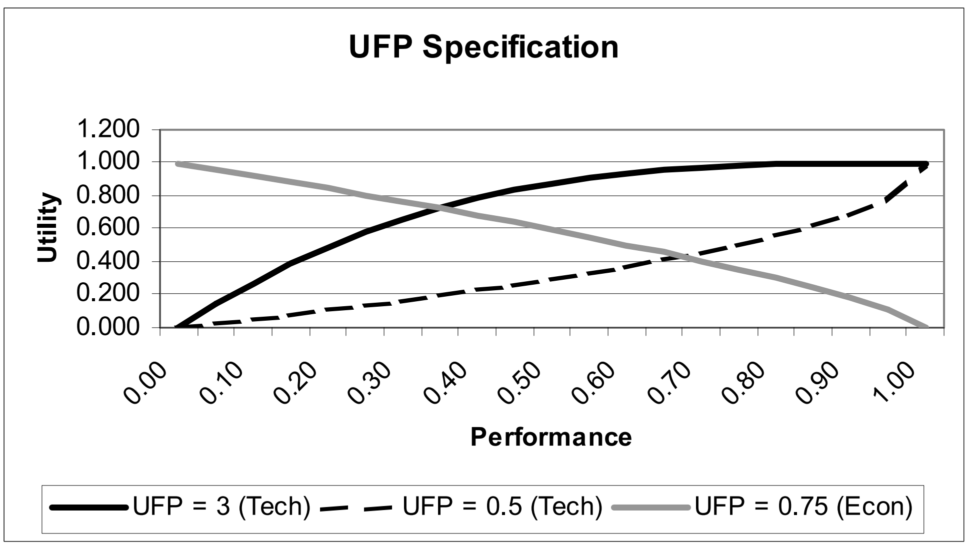

Figure 12. Adjusted Decision Maker Utility Functions

Table 9 shows that the decision maker has also adjusted his willingness to make trade-offs between the various MOPs. The asterisks beside the Weapons & Battle Management and Tactical Data Links entries in Table 3 indicate that these are key performance parameters (KPP) for the notional C2 system. Thus, the decision maker is less willing to make trade-offs with these MOPs (as indicated by the scaling constant values of 0.30). Finally, the schedule weighting factors are adjusted so that s = (0.5, 0.3,

0.2). This schedule weighting configuration implies that the decision maker places greater emphasis on delivering capability earlier, rather than later, in the system development.

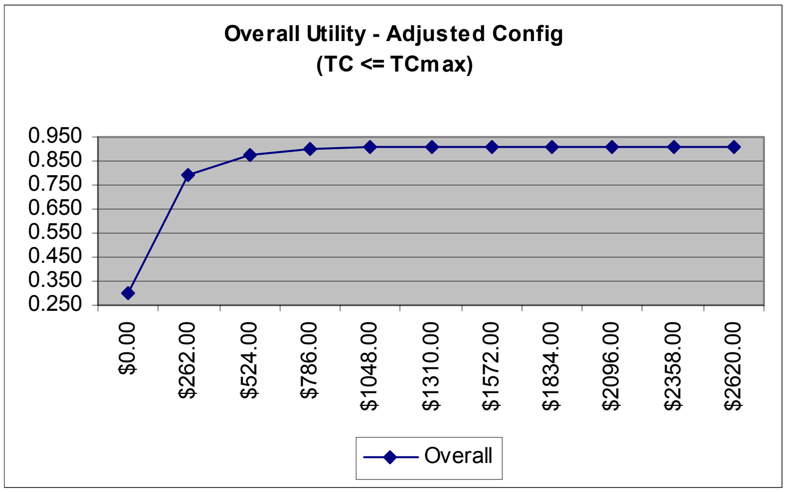

Figure 13. Overall Utility – Adjusted Configuration (Table 9)

Figure 13 displays the overall utility curve that results from the CAIV/EA model parameters specified by Table 9. The figure illustrates how as the design cost of the system begins to increase the decision maker's value of the design alternative improves rapidly. However, from approximately $1,048,000 to the cost ceiling of $2,620,000 the overall utility plateaus. This phenomenon is the result of the design cost constraint specified by Equation (17). In this mathematical program, the design cost must be less than or equal to the cost target. The plateau is caused by the diminishing marginal returns for the technical MOPs when compared to the increasing losses in economic MOP utility as the design cost target is increased. Thus, by specifying that the design cost must be less than or equal to the cost target the impact is a design cost that never increases beyond $1,048,000. In other words, the resulting payoff in terms of technical

performance does not offset the payoff in terms of cost. From an overall utility perspective, the optimization algorithm converges at $1,048,000.

To understand how the overall utility for the system behaves beyond this design cost, it is necessary to modify Equation (17). The cost constraint is changed to require the design cost be equal to the cost target. This modification forces the optimization algorithm to solve for design alternatives beyond the convergence point of $1,048,000. This modification is depicted by Figure 14.

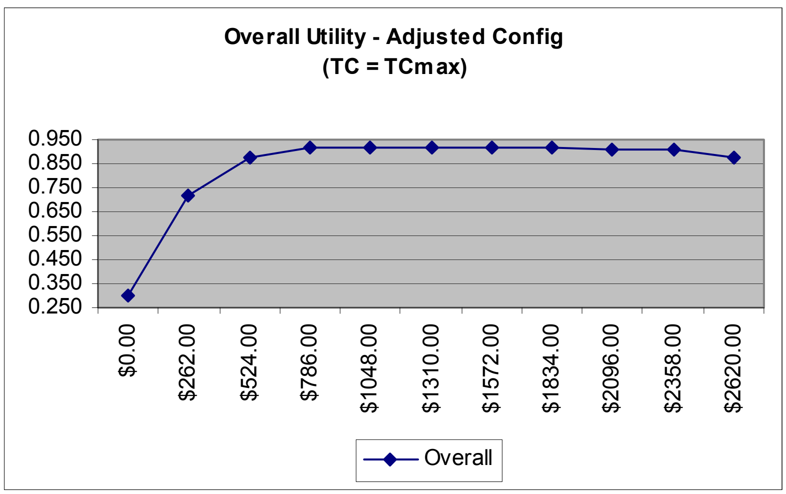

Figure 14. Modified Overall Utility – Adjusted Configuration (Table 9)

Figure 14 reveals a similar ramp-up in utility as was found in Figure 13. This ramp-up is also followed by a plateau (more on this to follow). However, unlike the previous chart, Figure 14 presents a region of declining overall utility towards the end of the design cost range. This region clearly illustrates the negative impact upon overall utility by increasing the design cost of the system.

Closer inspection of the overall utility plateau described in the previous paragraph reveals that this area is not truly a region of equivalent overall utilities. Instead, this region is really the peak of the overall utility curve. Zooming in on this region illustrates

that overall utility is increasing from $1,048,000 to $1,310,000 and then decrease beyond that point. Figure 15 presents the zoomed view of this region.

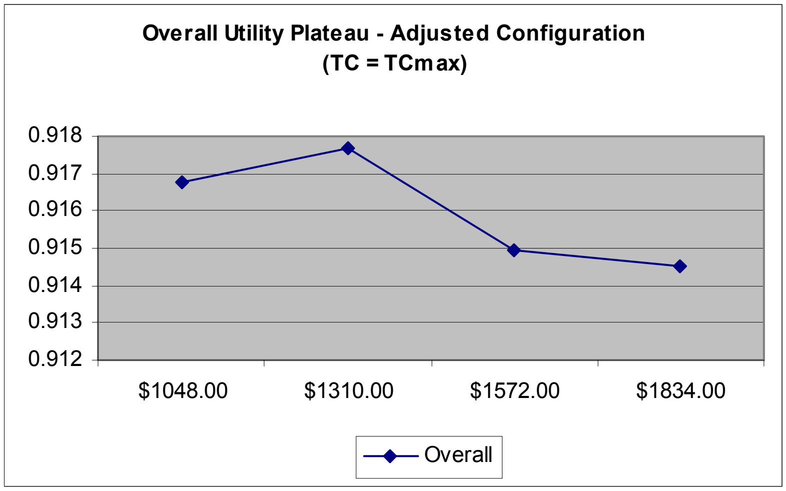

Figure 15. Overall Utility – Adjusted Configuration (Table 9)

Figure 15 shows that the optimization algorithm converges where the system cost is approximately $1,310,000. This is a greater alternative design cost than the one presented by the earlier model formulation where design cost could be less than or equal to the cost target. However, because system of constraints is not equivalent between the overall utility curves presented in Figures 13 and 14, the results are not directly comparable.

When evaluating the overall utility curve in Figure 15, it is important to keep the scale of the vertical axis in mind. The variations in this range are rather minute (less than four thousandths of overall utility separating the highest and lowest points). Therefore, the practical significance of the variation is limited. What is important is the ability to address the macro-level trend in the utility curve. Within a system cost range from approximately $1,048,000 to $1,834,000, a decision maker would not experience any major variations on overall utility for the system design alternatives generated by the

optimization algorithm. Thus, from a CAIV perspective, a cost target could be moved back from the peak (approximately $1,310,000) to the start of the plateau (at approximately $1,048,000) and overall decision maker satisfaction would remain constant. In making this decision, some time should be spent evaluating how the technical measures of performance score at the new cost target. However before doing so, some additional investigation will be made into the overall utility curve and how the technical MOPs behave across the entire cost range.

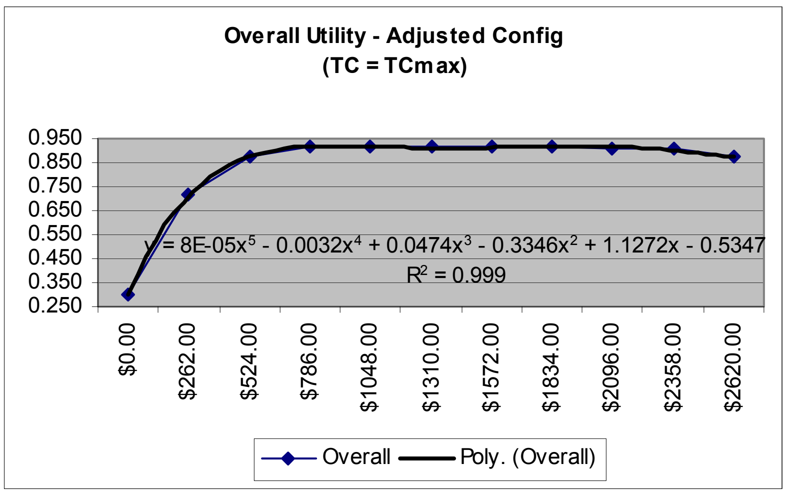

Figure 16. Adjusted Configuration (Table 9) Regression Model

Keeping in mind that one of the goals of this research is to be able to quantify the functional relationship between cost and overall decision maker satisfaction, the overall utility curve depicted in Figure 14 has been fit with polynomial regression line. The resulting function allows an analyst to estimate the rate of change in overall utility given and incremental change in the system cost (i.e., the first derivative of the regression line). This observation provides the decision maker with a first order capability to assess the impact of funding volatility upon the performance of the system.

To evaluate the change in system performance as a function of cost, it is valuable to examine how the technical MOPs behave across the entire cost range. Figures 17 through 19 present the relative performance levels for each of the MOPs in the three development increments.

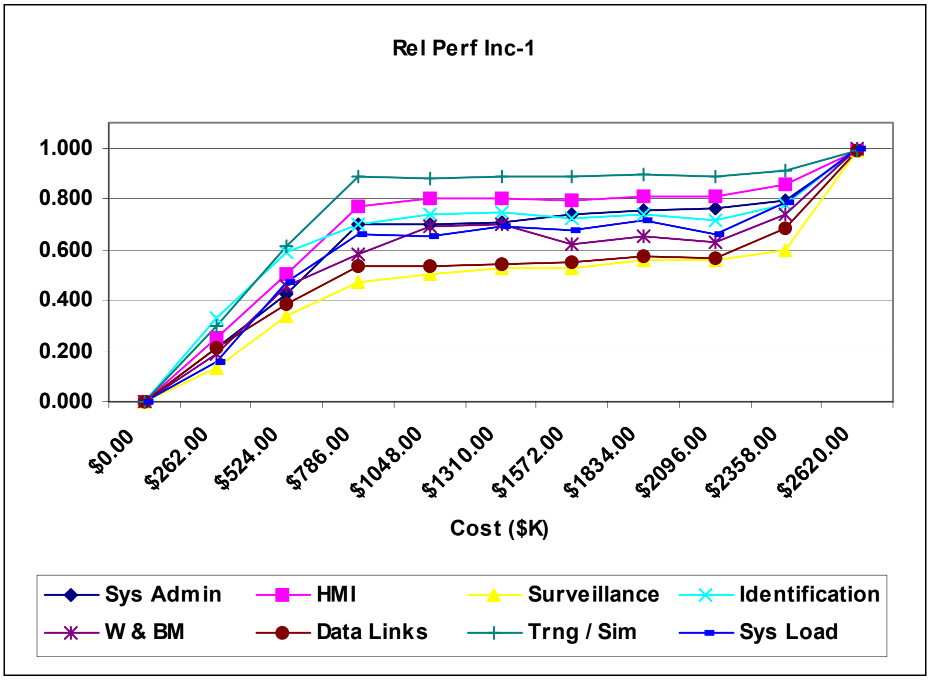

Figure 17. Technical Performance – Increment 1

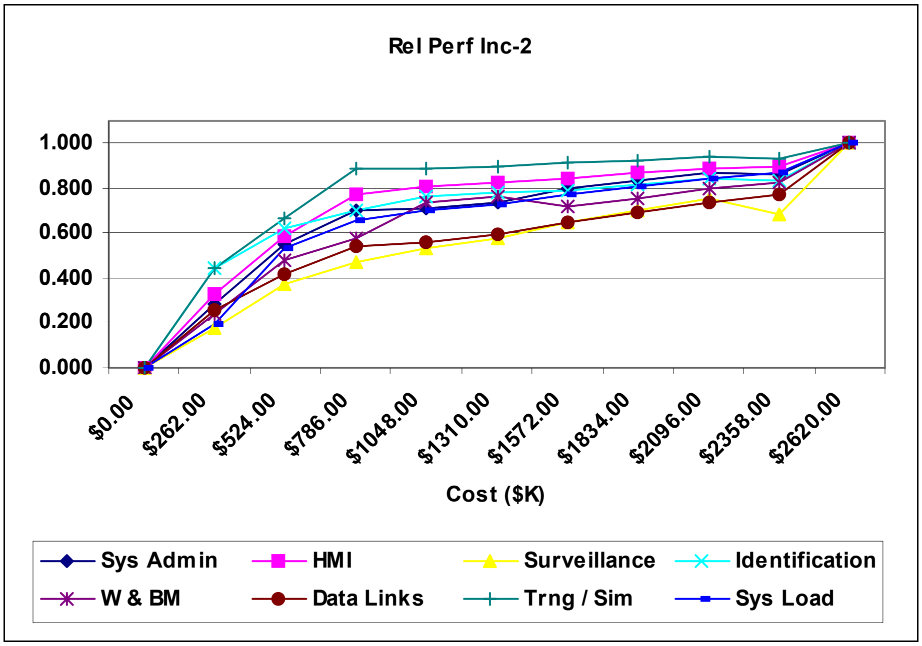

Figure 18. Technical Performance – Increment 2

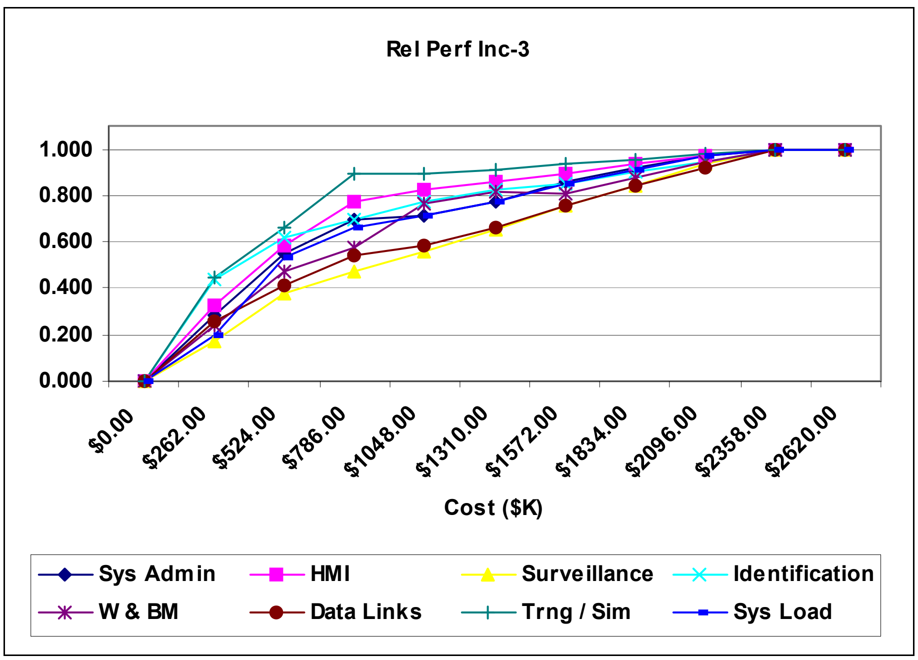

Figure 19. Technical Performance – Increment 3

The technical MOPs appear to behave in the expected manner. When the system cost target is equal to zero (0) there are no funds available to develop the system, thus all of the technical MOPs have performance levels of zero (0). As the cost target is increased, the relative performance levels for the technical MOPs increase as well. Some

of the MOPs improve in a linear manner with cost, while others take on non-linear forms. Because the model assumes that technical performance for a given MOP is cumulative, the relative performance for the later increments is always greater than or equal to the performance of earlier ones at a given cost target. Finally, when the system cost target equals the cost ceiling, all of the technical MOPs are at their objective level at the end of the first, core increment. In reality, there would be no need for the follow-on increments two and three.

Returning to the overall utility curve depicted in Figure 14, it appeared that a plateau in the function begins at approximately $1,048,000. This cost target will be used as the basis for the remaining portion of the initial analysis. When evaluating a single cost target, there are several points of interest. First, it is important to understand what the resulting system performance is at the specified target. Next, the phasing of the capability delivery is of interest (i.e., where in the development cycle are the technical MOPs met). Finally, identification of the cost drivers allows for an appreciation of where the budget is being allocated to create the resulting performance.

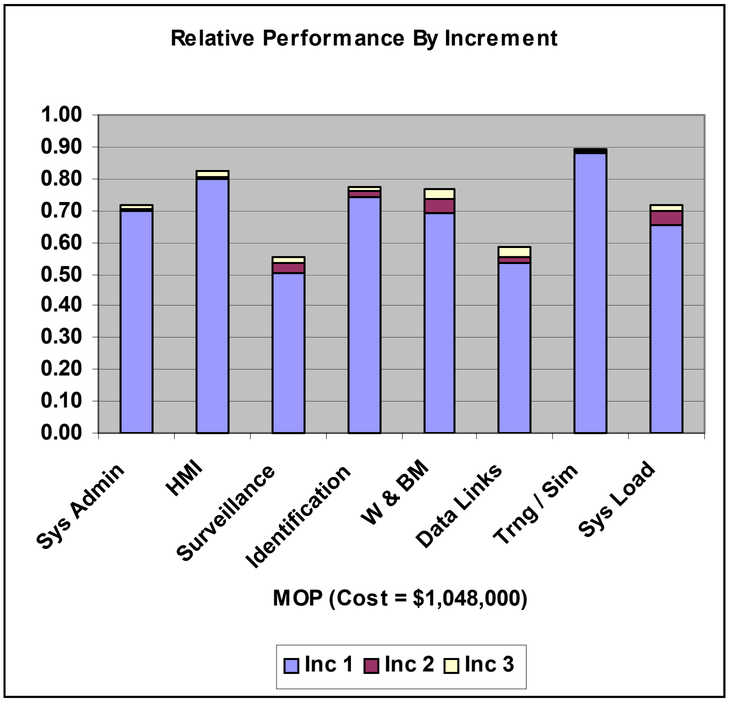

Figure 20. Relative Performance by Increment (Cost Target = $1,048,000)

Figure 20 depicts the relative performance for each of the technical MOPs generated by the design alternative (constrained by a cost target of $1,048,000). Each column is segmented by development increment. As the chart indicates, the preponderance of capability is delivered in the first development increment. This observation is consistent with the schedule weight scheme specified for the current configuration of the CAIV/EA model. Over half of the schedule weight is placed on the first increment. Thus a decision maker would be pleased to see that results from the model are consistent with their preferences. However, what may be of concern are the levels of implementation for the key performance parameters. While W&BM is over 75% implemented, Data Links is less than 60% implemented at this cost target. If these results are not acceptable, then the decision maker may want to reconsider the shape of his utility function or his preferences for trade-offs. A recursive process of preference

specification and results analysis should help the decision maker hone in on a design alternative that meets his requirements. The sensitivity analysis techniques presented in the next section might offer a means to decrease the amount of time needed to evaluate the results of the CAIV/EA model.

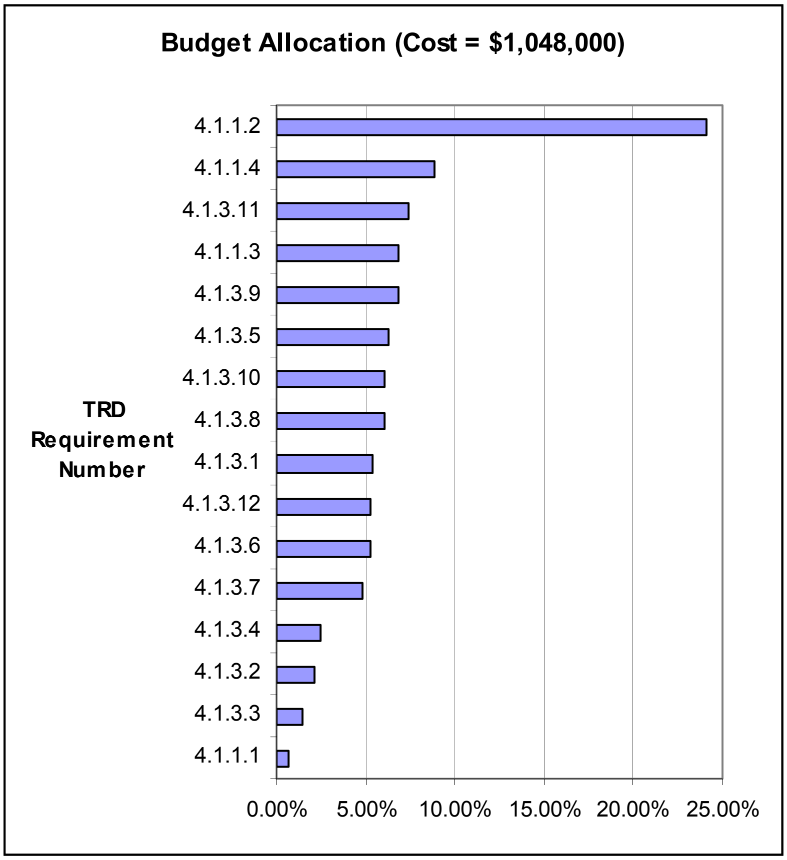

Figure 21. Cost Driver Identification (Cost Target = $1,048,000)

Figure 21 addresses the final portion of cost target evaluation. The chart lists the sixteen design attributes cited in Table 6 (the software functional requirements described in the system's technical requirements document). The list of design attributes has been sorted in descending order to show the relative distribution of the available budget. This distribution represents the design alternative determined by the CAIV cost target of $1,048,000. As the chart reveals, requirement 4.1.1.2 receives almost 25% of the entire

budget. This graphic is a valuable tool for understanding which design attributes are cost drivers in the system development. After identifying the relevant cost drivers for a system design, a development IPT should perform a sanity check to make sure that the CAIV/EA model's results are consistent and realistic.

This section has presented some initial analysis of the CAIV/EA model output data generated from the notional C2 system. Based upon this first round of analysis, some questions remain:

- When overall utility is equivalent, what is the resulting trade-off between cost and technical performance?
- How do variations in the schedule weighting factors affect the system design alternative (for a given cost target)?
- How influential are the single attribute scaling factors (k_i) in affecting the resulting capability for a design alternative (again, for a given cost target)?, and
- What is the influence of risk, design attribute maximums (Z_{jmax}), and the QFD matrix (R), upon the design alternative?

The following section presents additional analysis that attempts to answer each of these questions.

CAIV/EA Model Sensitivity Analysis

To evaluate the first question posed at the end of the previous section, the end points of the plateau region depicted in Figure 15 were used ($1,048,000 and $1,843,000) to specify the cost targets. Both of these cost targets generate an overall utility of approximately 0.915. Thus by holding this variable constant, it is possible to isolate the resulting trade-off between cost and performance.

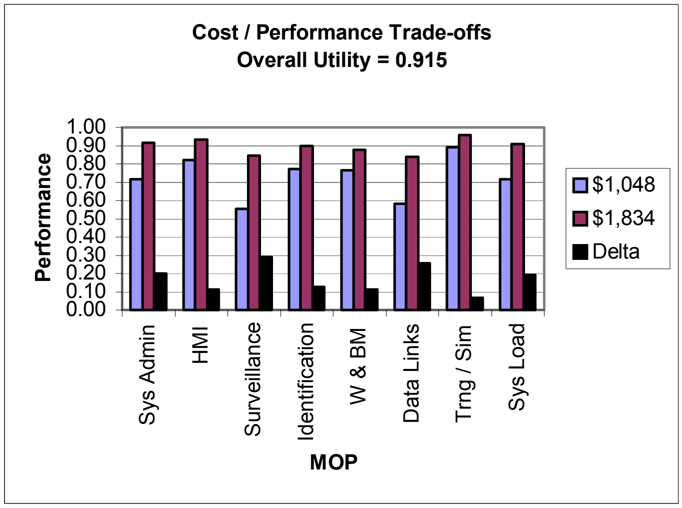

Figure 22. Cost / Performance Trade-offs with Equivalent Overall Utility

Figure 22 illustrates the levels of performance for each of the technical MOPs at the low and high ends of the overall utility plateau. As is to be expected, the lower cost target results in lower levels performance than the higher one. The series entitled “Delta” represents the difference between the higher and lower cost targets’ levels of performance for each technical MOP. Based upon the decision maker’s preferences (as specified in table 10), the design alternatives generated along the plateau are all equally satisfactory. In theory, the less expensive, lesser performing system is just as valuable or satisfactory to the decision maker as the more expensive, higher performing alternative. Thus, the delta values describe the available trade space between cost and performance. With this is mind, it is then necessary for the decision maker to review the relationships depicted in Figures 17 - 19 to understand how performance varies as a function of cost across this region of equivalent overall utility. Understanding these relationships allows the decision maker to decide if variations from the specified cost target result in any operationally significant changes to the system’s performance.

The next area of interest relates to how variations in the schedule weighting factors affect the system design alternative, at a given cost target. From a project management perspective, a program's schedule can be classified as aggressive (seeking the shortest schedule possible), conservative, or somewhere in between. Table 10 lists five different schedule weighting postures. The conservative posture places all of the weighting for overall utility upon the incremental utility from the final increment. Conversely, the aggressive posture places all of its weighting upon the incremental utility from the initial increment.

Table 10. Schedule Weighting Factors and Associated Postures

	Schedule Weighting Factor		
Description	**Inc 1**	**Inc 2**	**Inc 3**
Conserv.	0.00	0.00	1.00
Mod. Cons.	0.00	0.25	0.75
Moderate	0.25	0.50	0.25
Mod. Aggr.	0.75	0.25	0.00
Aggressive	1.00	0.00	0.00

As was defined in Chapter III, there is greater development risk associated with earlier development increments than with later ones. Thus when cost is held constant in the CAIV/EA model, one would expect the more conservative (i.e., longer) development schedule to result in higher levels of attainment for the technical MOPs than the aggressive posture. Figure 23 substantiates this assertion. This chart illustrates the trade-offs created between schedule and performance when cost is held constant (at the $1,048,000 cost target). The technical MOPs are displayed across the horizontal axis. Each MOP cluster contains five different series, representing the different schedule postures cited in table 10.

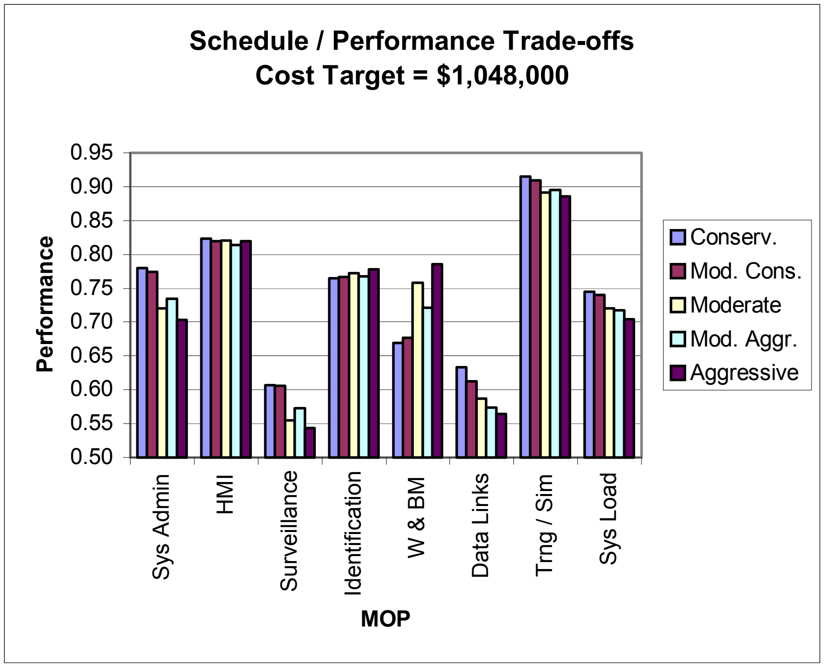

Figure 23. Schedule / Performance Trade-offs with Constant Cost Target

In line with the previous assumption, the technical MOPs in Figure 22 tend to degrade as the schedule posture progresses from a conservative to an aggressive alignment. A decision maker can use the results from this analysis to help to understand the effect of accelerating a development project under a CAIV constrained budget. From a modeling perspective, it is important that an analyst correctly captures the proposed EA strategy and applies the appropriate schedule weighting factors. Figure 22 clearly illustrates the potential impacts caused by variations in these parameters.

As Figure 23 demonstrates, five of the MOPs demonstrate a pronounced degradation. Two (HMI and Identification) stay relatively level (one slightly decrease while the other slightly improves). The final MOP (W&BM) exhibits significant improvement as the schedule tightens. This behavior seems contrary to the underlying assumption regarding schedule and performance trade-offs. However, it is important to remember that there are multiple parameters influencing the CAIV/EA model results (to

include the MOP scaling constants and the QFD matrix). The following sections will address the influence of these parameters.

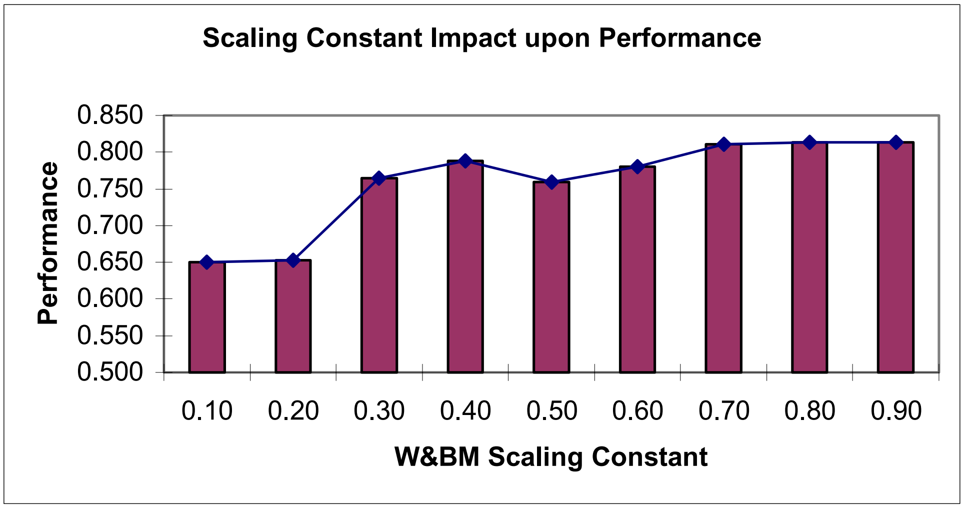

Figure 24. Scaling Constant Impact upon Performance for a Single MOP

Figure 24 illustrates the impact of scaling constant selection upon the level of performance for a single MOP, in this case W&BM. From the formulation presented in Chapter III, one would expect that as the value of the scaling constant increases in value its associated MOP should improve as well. The chart in Figure 24 supports this assertion. For W&BM, as the value of the scaling constant increases from 0.10 to 0.90, the level of performance tends to increase as well. It is important to remember that the variations in the W&BM scaling constant are made while holding all of the other scaling constants (as described in table 9) are held at their original values (i.e., the scaling constants remain constant). While this analysis does not examine the levels of performance for the other MOPs, it should be expected that in a CAIV cost constrained environment as W&BM improves the other technical MOPs degrade (i.e., there is trade-off incurred by improving the MOP) . An analyst must take care when eliciting the MOP scaling constant values from the decision maker. A decision maker should be aware that

the overall system does not necessarily improve by artificially inflating the scaling constant associated with a single MOP.

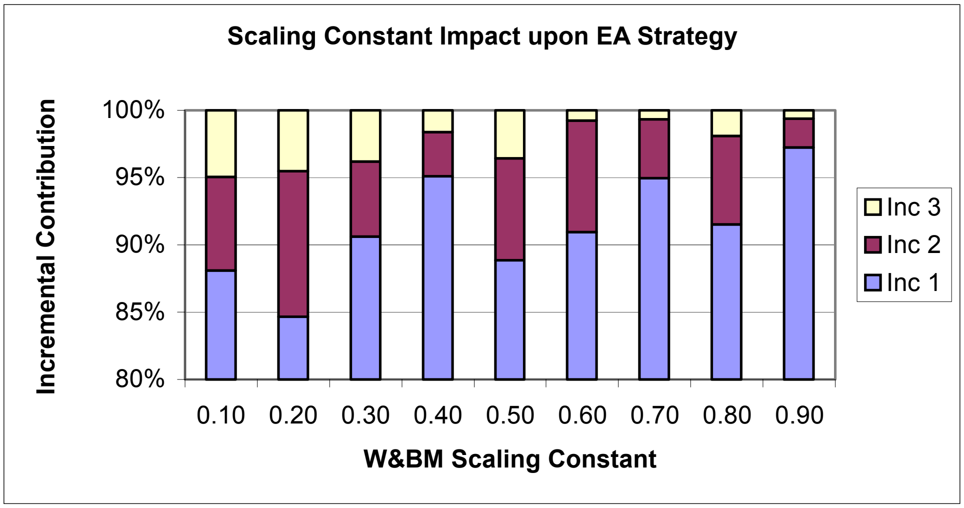

Figure 25. Scaling Constant Impact upon EA Strategy for a Single MOP

While remaining focused upon the impact of scaling constant selection, it is of interest to examine how the EA strategy is impacted. Again, from the CAIV/EA formulation specified in Chapter III, one would expect that as the scaling constant for a given technical MOP increases in value, the proportion of capability delivered earlier in the development cycle will increase and the proportion delivered later in the development will decrease. Figure 25 supports this interpretation. The chart illustrates how as the value for the W&BM scaling constant increases, the proportion of capability for the MOP delivered in earlier increments generally increases while the proportion delivered in later increments generally decreases. Just as with the previous example, the other scaling constants are not changed during the analysis (only W&BM is modified). Thus, from a CAIV/EA trade-off perspective it must be expected that as the delivery schedule for one MOP improves there are other MOPs that are delayed and delivered later. The same warnings to the analyst and the decision maker mentioned previously hold in this case as

well. Inflating the scaling constant to improve the delivery for one MOP implicitly degrades the delivery of one or more of the remaining MOPs.

The final questions addressed in this section relates to influence of risk, design attribute maximums (Z_{jmax}), and the QFD matrix (R), upon the design alternative. Up until this point, we have been primarily concerned with the influence of model parameters upon the resulting system performance. It is important to remember that system performance is ultimately a function of the levels of the design attributes (as specified in Equation (17)). Therefore, to truly have an appreciation for how the selection of CAIV/EA model parameters influences system performance, it is important to evaluate how the design attribute selection is influenced as well. A regression of several design attribute associated parameters (upon the resulting level of attainment at the end of the final EA increment) will be used to illustrate their influence. Although this analysis is completely deterministic in nature, regression offers an efficient means to understand the significance of each of the parameters.

The first parameter of interest is the relationship between a given design attribute and the technical MOPs. The technical measures of performance for the test case are linked to the design attributes through the QFD matrix specified in table 7. By summing the elements for each row of the matrix it is possible to generate a value that describes the magnitude of the relationship for the DA and the technical MOPs. By comparing the row sum values for each of the design attributes, it is possible to determine on a relative scale which has the strongest relationship with technical MOPs and which has the weakest. Thus, the row sum of the QFD matrix for a given DA will be used as an independent variable in the regression that follows shortly.

The next parameter to be evaluated is the vector describing the design attribute maximums (Z_{jmax}). Because all of the design attributes in the test case are described in terms of source lines of code (SLOC), it is possible to draw one-to-one comparisons between each. Those design attributes with larger maximum values may draw upon more resources than those with smaller maximums. The design attributes with lower maximums might improve overall system performance more rapidly than those with larger maximum values. Therefore, to understand the roles of this parameter, it too will be included as an independent variable in the regression.

The final parameter to be evaluated is the matrix describing the design attribute risk factors (table 8). Because risk is quantified as a unit-less value that influences the realized level of attainment for a given design attribute in a given increment, it is also possible to draw one-to-one comparisons. To generate a single, composite risk value for each design attribute, the product of the risk factors for each increment is taken. Those design attributes with larger risk factors may draw upon more resources than those with smaller risk factors. The design attributes with lesser risk factors might improve overall system performance more economically in earlier development increments than those with larger maximum values. Thus, the composite risk factor is included as an independent variable in the regression.

The dependent variable selected for the regression is the relative level of attainment for the design attributes at the end of the third development increment. While any of the three increments could be examined, this analysis has chosen to simply examine the resulting level of attainment occurring at the completion of the EA development cycle. Preliminary analysis reveals that taking the natural logarithm of the

dependent variable improves the inferential results of the regression model (this is a common transformation used in linear regression). Therefore, this transformation has been used in the ensuing analysis. Finally, a fourth independent variable has been added to account for the interaction between design attribute maximums and their corresponding QFD matrix row sum.

Table 11. Design Attribute Parameter Regression Data.

j	TRD Req#	Inc 3 Rel DA	ln(Inc 3 Rel DA)	SLOC	Row Sum	Comp Risk	SLOC * Row Sum
1	4.1.1.1	0.0264	-3.6339	2800	13	0.0000066	36400
2	4.1.1.2	0.7472	-0.2914	2800	24	0.0005540	67200
3	4.1.1.3	1.0000	0.0000	700	13	0.0000255	9100
4	4.1.1.4	1.0000	0.0000	700	18	0.0222943	12600
5	4.1.3.1	0.1742	-1.7476	2700	22	0.0035762	59400
6	4.1.3.2	0.0847	-2.4684	2700	17	0.0002225	45900
7	4.1.3.3	0.0588	-2.8330	2700	16	0.0000590	43200
8	4.1.3.4	0.0985	-2.3172	2700	21	0.0000000	56700
9	4.1.3.5	1.0000	0.0000	720	20	0.0000000	14400
10	4.1.3.6	1.0000	0.0000	540	17	0.0003935	9180
11	4.1.3.7	1.0000	0.0000	540	12	0.0000280	6480
12	4.1.3.8	1.0000	0.0000	540	13	0.0002260	7020
13	4.1.3.9	1.0000	0.0000	540	26	0.0057422	14040
14	4.1.3.10	1.0000	0.0000	540	32	0.0001549	17280
15	4.1.3.11	1.0000	0.0000	540	29	0.0003982	15660
16	4.1.3.12	1.0000	0.0000	540	12	0.0000001	6480

Table 11 presents the data used in the ensuing regression. The shaded column represents the natural log transformed increment three relative design attribute level data, used as the dependent variable. The four columns to the right of the shaded column contain the data for the independent variables: design attribute maximums (SLOC), the row sum of the QFD matrix for the given DA, the design attribute's composite risk factor, and the interaction term.

Table 12. Design Attribute Regression Results

Regression Statistics	
Multiple R	0.97675
R Square	0.95404
Adjusted R Square	0.93733
Standard Error	0.32184
Observations	16

ANOVA

	df	SS	MS	F	Significance F
Regression	4	23.65141	5.91285	57.08258	0.00000
Residual	11	1.13943	0.10358		
Total	15	24.79084			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	1.82262	0.41146	4.42962	0.00101	0.91700	2.72824
SLOC	-0.00316	0.00033	-9.58288	0.00000	-0.00389	-0.00244
Row Sum	-0.06495	0.02003	-3.24281	0.00783	-0.10903	-0.02087
Comp Risk	3.63403	15.06831	0.24117	0.81386	-29.53112	36.79919
SLOC * Row Sum	0.00011	0.00002	6.71255	0.00003	0.00008	0.00015

Table 12 presents the results generated by the regression of the four independent variables. Because this regression is a product of deterministically generated data, the analysis will not spend a large amount of time reviewing the statistical underpinnings. Instead, the data presented in Table 12 is used to determine if the parameters influence the level of attainment for the design attributes, and if so, which ones. The F-statistic value of 57.08 (p-value << 0.05) indicates that the parameters (i.e. the independent variables) have an influence upon the dependent variable. In fact, the significance of this value reveals that these variables have a very strong influence on determining the level of attainment.

Knowing that these parameters play an important role, it is also essential to understand which are most influential. The p-values for the individual model effects are reviewed to assist with this determination. The design attribute maximum variable (SLOC) and the interaction term (SLOC * Row Sum) have parameter estimates with the smallest p-values. Therefore, these parameters have an influential role in affecting the

levels of the design attributes. The QFD matrix row sum variable has a slightly larger p-value, but is still very significant. Finally, the composite risk variable has a very high p-value. Thus, it can be inferred from this regression that the risk variable is not as influential as the others.

From a modeling perspective, an analyst should use the results from this regression to emphasize specific areas when formulating a CAIV/EA model. Special attention should be paid to evaluating the design attribute vector maximum values. Additionally, the analyst should work closely with the development IPT to carefully generate the values to be used in the QFD matrix.

V. Conclusions

Overview

This chapter begins with a review of the research questions and objectives presented in Chapter I. It then demonstrates how the methodology and results presented in Chapters III and IV satisfy these questions and objectives. Next, an overarching process is presented to assist a development IPT with incorporating the CAIV/EA model into their acquisition planning activities. Finally, some limitations of the CAIV/EA model are discussed and some areas requiring future investigation are presented.

Accomplishment of Research Objectives and Questions

Chapter I posed the following question: “Is it possible to develop a process that integrates CAIV objectives with the EA framework?” If possible, such a process would help a user accomplish the following objectives:

- Better allocation of constrained resources,
- More efficient response to fluctuations in program funding, and
- Assist planning for future development activities (i.e., increments).

Pursuant to these objectives, the following questions were raised:

1. How might one generate and graphically depict the relationship between system cost and performance for a defense program?
2. What is the marginal benefit (or detriment) to a weapon system’s performance given an increase (or decrease) in funding beyond a cost objective?
3. How might one optimally allocate resources across a program planning horizon spanning several increments?

Through the use of several analytical techniques, this research has endeavored to logically integrate the characteristics of CAIV and EA into a single, unified mathematical model. The mathematical program specified in Equation (17) provides a rigorous approach to conducting CAIV cost/performance/schedule/risk trade-offs in an EA environment characterized by multiple development increments.

Via the CAIV/EA model formulation in Chapter III, pertinent data were generated, collected, and presented in Chapter IV. The data directly responds to the three questions posed above. The various charts and figures clearly illustrate how the outputs from the CAIV/EA model can show the functional relationship between a system's performance and its cost. By incrementally varying the cost of the system, it is possible to use the CAIV/EA model to estimate how the various measure of performance will respond to these changes. Finally, through the use of utility theory and optimization techniques it is possible to formulate a resource allocation scheme that translates the desired cost target into a system design alternative which satisfies the user.

The CAIV/EA model formulation easily integrates into a spreadsheet environment. In fact, all of the analysis conducted in Chapter IV was accomplished on a standard Microsoft Windows based personal computer (circa 2001 technology). This portability facilitates the use of the CAIV/EA model in the DoD program management environment. It is hoped that by using the approach specified in this research that more informed decisions regarding CAIV and EA are made (thus meeting the three goals specified above).

Integrated CAIV/EA Analysis Process

Having formulated and demonstrated the CAIV/EA model in the previous chapters, it is important to present a top-level process that a development IPT can use to incorporate the model with their existing program planning and analysis processes. Specifically, this process must integrate with the spiral development model described in Figure 2. Figure 2 specifies an iterative process that requires risk analysis and cost / performance trade-offs in each revolution of the development spiral. The CAIV/EA model integration process described in Figure 26 accomplishes these activities within the overarching EA strategy framework.

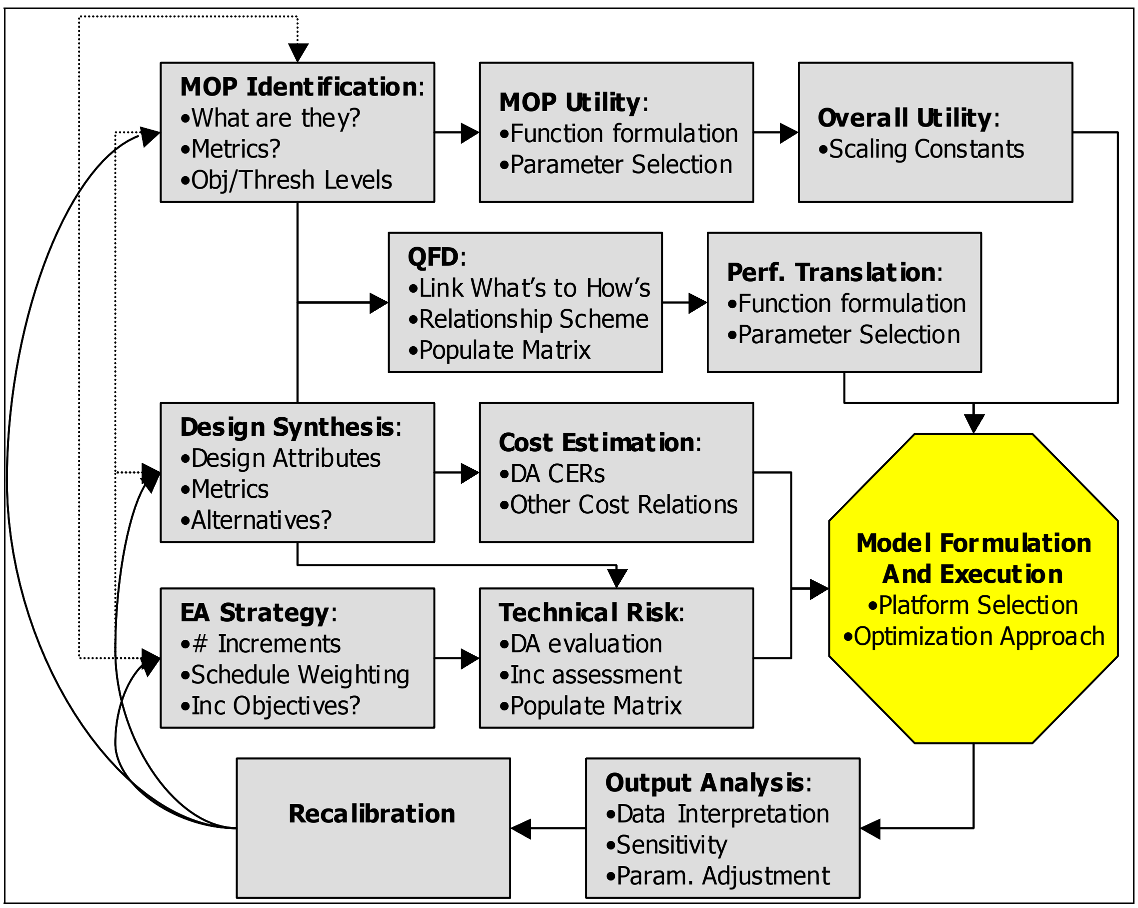

Figure 26. CAIV/EA Model Integration Process

The goal of this process is to gather the data required to build a CAIV/EA model that is specific and relevant to the current state of the weapon system's development. Having built the relevant model, it can then be exercised to generate trade-off data. This data is intended to assist the ensuing spirals' decision making and planning activities. After a spiral is accomplished, the actual results from that activity are incorporated with any new changes to the model's parameters to bring it (the CAIV/EA model) in line with the new development state. This iterative process tracks with the spiral development process demonstrated in Figure 2.

The CAIV/EA model integration process begins accomplishing three activities in tandem: MOP identification, design synthesis, and EA strategy definition. The first activity, MOP identification, relates to defining the individual technical measures of performance for the weapon system. Metrics are established for each MOP. Finally, overall threshold and objective levels of performance are established for the intended system end state.

Design synthesis pertains to accomplishing the systems engineering activities necessary to transform the user's operational requirements into definitive system architecture. Within the system architecture, design attributes are identified and described in quantitative terms. Finally, alternative solutions to the design attributes (where applicable) are developed.

The EA strategy definition activity involves specifying parameters associated with the overarching EA approach. These parameters include understanding the desired number of development increments and the schedule weighting preferences associated

with each. Additionally, any incremental threshold or objective levels of performance must be identified.

While each is a distinct activity in its own right, there is a certain degree of dependency between the three. For example, the system measures of performance may have some influence on determining viable design alternatives. Additionally, the threshold and objective levels of performance required for each increment in the EA strategy are tied to the initial definition of the MOPs. These dependencies are illustrated by the dotted lines in Figure 26. The interdependency of these three initial activities reinforces the need to use an IPT approach when integrating the CAIV/EA model. An analyst should not expect to build the model on his own. Additionally, no single stakeholder or functional area should dominate any one of these activities. Instead, there should be strong involvement from the user, systems engineering, and program management communities at all times.

Having accomplished the initial CAIV/EA model integration activities, it is now possible to begin those remaining activities needed for complete model formulation. Beginning with the system's MOPs, the analyst must select a utility function to model the decision maker's value system for each of the measures of performance (the test case uses the CDF for the standard Beta function, but there are other alternatives). Next, working with the decision maker, the analyst must elicit a shape for each utility function (in the test case this was accomplished via the utility function parameter, UFP). Finally, the overall utility function must be synthesized by eliciting the decision maker's willingness to make trade-offs between each of the MOPs. The values for the single

attribute scaling constants used in the overall utility function are a result of this elicitation.

Next, the activities needed to translate the system design into the various measures of performance must be accomplished. The QFD matrix linking the MOPs (the "what's") to the design attributes (the "how's") is established. A QFD relationship scheme must be selected. This scheme describes the numerical basis for assessing the strength of the relationships between the MOPs and the design attributes. Next, each MOP / DA pair is evaluated and its corresponding element in the QFD matrix is assigned a value. Finally, a performance translation function must be selected to transform the relative performance generated from the QFD matrix into an absolute value consistent with the units of the MOP.

The system design is then evaluated from a cost estimation perspective. Each of the design attributes is reviewed and an appropriate cost estimating methodology or relationship is applied to each. The level of cost detail required from CAIV/EA model will dictate how the resulting design alternative cost is calculated. In some situations it may only be necessary to take into consideration the direct costs associated with the design attributes. In other instances, the analyst may decide to include other "indirect" or "below the line" costs as well. Regardless, it is important that a single, consistent cost ceiling be calculated for the system. This cost ceiling is used in formulating the utility function for the economic MOP.

Finally, each of the design attributes must be evaluated for their associated technical risk. These evaluations are used to populate the elements of the incremental

risk matrix. The basis for this evaluation should be agreed upon by the members of the IPT and remain as consistent as possible during the development cycle.

It is now possible to synthesize all of the data and parameters collected during these initial steps into a single model. The analysts should determine the appropriate platform for the modeling (the test case used Microsoft Excel 2000®). Additionally, an optimization algorithm or application is required to determine the optimal design alternatives. It may also be necessary to use some degree of automation or scripting to assist with the model execution (the test case used Microsoft Visual Basic for Applications®).

Having completely formulated and implemented the model, it is now possible to extract the data needed to assist with the development's cost/performance/schedule trade-off decisions. Chapter IV presented several candidate data products (overall utility, performance as a function of cost, etc.). However, an analyst should determine what data is required by the decision maker and tailor the data products accordingly. Within Chapter IV there are several examples of sensitivity analysis. The analyst should conduct sufficient "what-if" analysis to help illustrate the influence of the decision maker's preferences (as well as other model parameters) upon the resulting system alternative.

Following the execution of the development activity, the "real world" data should be collected and used to recalibrate the CAIV/EA model. Such data might entail the true level of attainment for each of the design attributes and the true level of performance for each of the MOPs. There might be changes in the decision maker's valuation of the different MOPs as well. In short, all of the CAIV/EA model parameters and inputs must

be constantly evaluated to help maintain the relevance of the model. In doing so, the data generated should retain its value to the decision making process.

CAIV/EA Model Limitations

While this research has endeavored to create as robust and general of a model as possible, there are some inherent limitations. This section will attempt to address the major limitations. Additionally, some recommendations for further investigation will be presented. It is imagined that many of these limitations might be resolved through minor modifications to the current formulation.

Of greatest concern is the strict deterministic nature of the CAIV/EA model. The formulation as presented in Chapter III does not provide any opportunity to account for uncertainty in the model's parameters. Unfortunately, this limitation is not consistent with the basic nature of the model. This model is intended to be used assist the development planning of unique, military focused systems. Because these systems do not yet exist, the characteristics of their design and the risk associated with their development must be estimated. Additionally, the methodologies used to estimate the cost of the design alternatives are also based upon estimates. Thus, the current CAIV/EA model should be adapted to address the uncertainty surrounding these estimates. A Monte Carlo simulation approach might be integrated to resolve this limitation. Such an approach would be an improvement upon the model's current implementation of risk. Instead of explicitly addressing risk through the incremental risk matrix, it would be implicitly incorporated via the variance estimates of the input parameters (specifically the design attribute maximums).

Another general limitation of the model is its "development-centric" emphasis. As it stands, the CAIV/EA model does not integrate any life-cycle cost factors (i.e., maintenance, operations and supports, etc) into its formulation. Instead, the model focuses solely on only those costs associated with developing the design. History dictates that the preponderance of resources spent on a weapon system occur after it has been fielded and while it is being sustained. Thus, the model should be expanded to attempt to capture the impacts of a design alternative upon not just its development cost, but also its production and operational support cost. This expanded model would seek to balance the overall life-cycle cost with the decision maker's perceived value of the system performance (as opposed to simply balancing the benefits with the development costs).

Of final concern is the manner in which performance levels are translated from the attained levels for the design attributes. The current formulation translates a relative level of performance from the relative levels of attainments for the design attributes. This translation is accomplished via the QFD matrix. The formulation found in Chapter III uses the strength of the relationships between the MOP/DA pairs as the basis for the translation. However, the translation does not account for the correlations between the each of the design attributes. Traditionally, these correlations compose the "roof" of the house of quality. In some situations, improvements in one design attribute might implicitly improve another design attribute. Conversely, increase in a given design attribute might degrade the level of another design attribute. Fung et al. (2002) present a candidate approach for addressing these correlations and using them to optimize design selection. This methodology might be considered to improve the quality of trade-offs made by the CAIV/EA model.

Summary

This chapter has demonstrated how the objectives stated at the beginning of the research have been met. A process has been developed that clearly incorporates the goals of CAIV analysis into an EA framework. Finally, the known limitations of the CAIV/EA model have been addressed and recommendations for improvements have been presented.

Often, DoD acquisition directives are issued using broad, subjective terms with little guidance to assist their "real world" implementation. The result is crippling confusion resulting from acquisition professionals knowing "what" they are supposed to do, but not knowing "how" to do it. This characterization is accurate for both CAIV and EA.

While the approach described in this research is not panacea, it does provide the DoD acquisition community (i.e., users, program managers, cost analysts, etc.) with a disciplined, quantitative method to satisfy the spirit of the USD(AT&L) direction on CAIV and EA plans. Additionally, the work goes a step further by identifying a technique for integrating the two initiatives. In other words, this research recognizes the interdependent relationships between program forces (i.e., cost, schedule, performance, and risk) and attempts to rigorously trade-off these elements to optimize overall user satisfaction. In short, the method presented herein is an answer to the question of "how" to implement and integrate CAIV and EA. By adopting this approach, it is hoped that better acquisition decisions are made, resources are allocated more efficiently, and the user receives an operationally effective and suitable system.

Appendix A. CAIV/EA Model Spreadsheet Implementation (Screen shots)

Model Summary Data

	Relative Performance				MOP Factors		
MOP(i)	**Name:**	**Inc 1**	**Inc 2**	**Inc 3**	**PFP**	**UFP**	**ki**
1	Sys Admin	0.71	0.75	0.75	1.00	1.00	0.10
2	HMI	0.76	0.80	0.81	1.00	1.00	0.10
3	Surveillance	0.49	0.55	0.58	1.00	1.00	0.10
4	Identification	0.70	0.74	0.76	1.00	1.00	0.10
5	W & BM	0.57	0.64	0.68	1.00	1.00	0.30
6	Data Links	0.51	0.58	0.59	1.00	1.00	0.30
7	Trng / Sim	0.88	0.90	0.90	1.00	1.00	0.10
8	Sys Load	0.66	0.72	0.73	1.00	1.00	0.10
9	Cum Cost	771.71	975.75	1048.00	1.00	1.00	0.30

	Increment 1	Increment 2	Increment 3
Inc Utility	0.733	0.758	0.767
Sch Wght	0.33	0.33	0.33
Overall Utility	0.753		

	Increment 1	Increment 2	Increment 3
Inc Cost	$771.71	$204.04	$72.25
Cum Cost	$771.71	$975.75	$1,048.00
Total Cost	$1,048.00		

Cost Ceiling	$2,620.65
Cost Target	$1,048.00
DesignCost	$1,048.00

	A	B	C	D	E	F	G	H	I	J	K
1	**Increment 1**										
2	**MOP(i)**	**Name:**	**Rel Perf**	**PFP**	**Thrsh**	**Obj**	**Abs Pef**	**UFP**	**Util-Raw**	**ki**	**Util-Scaled**
3	1	Sys Admin	0.71	1.00	0.00	1.00	0.71	1.00	0.71	0.10	0.95
4	2	HMI	0.76	1.00	0.00	1.00	0.76	1.00	0.76	0.10	0.95
5	3	Surveillance	0.49	1.00	0.00	1.00	0.49	1.00	0.49	0.10	0.97
6	4	Identification	0.70	1.00	0.00	1.00	0.70	1.00	0.70	0.10	0.95
7	5	W & BM	0.57	1.00	0.00	1.00	0.57	1.00	0.57	0.30	0.89
8	6	Data Links	0.51	1.00	0.00	1.00	0.51	1.00	0.51	0.30	0.90
9	7	Trng / Sim	0.88	1.00	0.00	1.00	0.88	1.00	0.88	0.10	0.94
10	8	Sys Load	0.66	1.00	0.00	1.00	0.66	1.00	0.66	0.10	0.96
11	9	Cum Cost			0.00	2620.65	771.71	1.00	0.71	0.30	0.86
12										**K**	-0.65
13										**UI(x)**	0.733
14											
15	**Increment 2**										
16	**MOP(i)**	**Name:**	**Rel Perf**	**PFP**	**Thrsh**	**Obj**	**Abs Pef**	**UFP**	**Util-Raw**	**ki**	**Util-Scaled**
17	1	Sys Admin	0.75	1.00	0.00	1.00	0.75	1.00	0.75	0.10	0.95
18	2	HMI	0.80	1.00	0.00	1.00	0.80	1.00	0.80	0.10	0.95
19	3	Surveillance	0.55	1.00	0.00	1.00	0.55	1.00	0.55	0.10	0.96
20	4	Identification	0.74	1.00	0.00	1.00	0.74	1.00	0.74	0.10	0.95
21	5	W & BM	0.64	1.00	0.00	1.00	0.64	1.00	0.64	0.30	0.87
22	6	Data Links	0.58	1.00	0.00	1.00	0.58	1.00	0.58	0.30	0.89
23	7	Trng / Sim	0.90	1.00	0.00	1.00	0.90	1.00	0.90	0.10	0.94
24	8	Sys Load	0.72	1.00	0.00	1.00	0.72	1.00	0.72	0.10	0.95
25	9	Cum Cost			0.00	2620.65	975.75	1.00	0.63	0.30	0.88
26										**K**	-0.65
27										**UI(x)**	0.758

	A	B	C	D	E	F	G	H	I	J	K
28											
29	**Increment 3**										
30	**MOP(i)**	**Name:**	**Rel Perf**	**PFP**	**Thrsh**	**Obj**	**Abs Pef**	**UFP**	**Util-Raw**	**ki**	**Util-Scaled**
31	1	Sys Admin	0.75	1.00	0.00	1.00	0.75	1.00	0.75	0.10	0.95
32	2	HMI	0.81	1.00	0.00	1.00	0.81	1.00	0.81	0.10	0.95
33	3	Surveillance	0.58	1.00	0.00	1.00	0.58	1.00	0.58	0.10	0.96
34	4	Identification	0.76	1.00	0.00	1.00	0.76	1.00	0.76	0.10	0.95
35	5	W & BM	0.68	1.00	0.00	1.00	0.68	1.00	0.68	0.30	0.87
36	6	Data Links	0.59	1.00	0.00	1.00	0.59	1.00	0.59	0.30	0.88
37	7	Trng / Sim	0.90	1.00	0.00	1.00	0.90	1.00	0.90	0.10	0.94
38	8	Sys Load	0.73	1.00	0.00	1.00	0.73	1.00	0.73	0.10	0.95
39	9	Cost			0.00	2620.65	1048.00	1.00	0.60	0.30	0.88
40										**K**	-0.65
41										**UI(x)**	0.767

	A	B	C	D	E	F	G	H	I	J	K	L
57												
58	QFD Matrix			Inc 3	0.75	0.81	0.58	0.76	0.68	0.59	0.90	0.73
59				Inc 2	0.75	0.80	0.55	0.74	0.64	0.58	0.90	0.72
60				Inc 1	0.71	0.76	0.49	0.70	0.57	0.51	0.88	0.66
61				MOP(i)	1	2	3	4	5	6	7	8
62												
63				Col Sum	29	44	41	32	36	42	25	56
64	Design Attributes (DA)				Measures of Performance (MOP)							
65		j	TRD Req#	SLOC	Sys Admin	HMI	Surveillance	Identification	V & BM	Data Links	Trng / Sim	Sys Load
66		1	4.1.1.1	2800	1	0	3	3	1	3	1	1
67		2	4.1.1.2	2800	0	3	3	3	9	3	0	3
68		3	4.1.1.3	700	1	1	1	3	1	3	0	3
69		4	4.1.1.4	700	0	0	3	1	3	1	1	9
70		5	4.1.3.1	2700	1	3	1	1	3	9	1	3
71		6	4.1.3.2	2700	1	1	9	1	1	1	0	3
72		7	4.1.3.3	2700	3	3	3	1	1	3	1	1
73		8	4.1.3.4	2700	3	1	3	1	1	3	0	9
74		9	4.1.3.5	720	1	9	1	1	3	3	1	1
75		10	4.1.3.6	540	3	1	1	3	3	3	0	3
76		11	4.1.3.7	540	0	3	3	1	0	1	1	3
77		12	4.1.3.8	540	1	1	0	1	3	1	3	3
78		13	4.1.3.9	540	3	3	3	1	3	3	1	9
79		14	4.1.3.10	540	1	3	3	9	3	3	9	1
80		15	4.1.3.11	540	9	9	3	1	0	1	3	3
81		16	4.1.3.12	540	1	3	1	1	1	1	3	1

Peformance Translation

		Incremental Design Attainment															Design Attribute Cost					
65	Row Sum	Inc 1 Planned	Inc 1 DA Risk	Inc 1 Attained	Inc 1 DA Total	Inc 2 Planned	Inc 2 DA Risk	Inc 2 Attained	Inc 2 DA Total	Inc 3 Planned	Inc 3 DA Risk	Inc 3 Attained	Inc 3 DA Total	Inc 1 Rel DA	Inc 2 Rel DA	Inc 3 Rel DA	Inc 1 Cost	Inc 2 Cost	Inc 3 Cost	j	CERs:	Factor
66	13	0.00	0.13	0.00	0.00	407.80	0.01	404.09	404.09	161.88	0.01	161.00	565.10	0.00	0.14	0.20	$0.00	$36.53	$14.50	1	Productivity	216.2
67	24	23.72	0.31	16.45	16.45	598.98	0.06	564.24	580.69	403.76	0.03	391.17	971.86	0.01	0.21	0.35	$2.12	$53.66	$36.17	2	Labor Rate	$19.37
68	13	805.34	0.13	700.00	700.00	0.00	0.05	0.00	700.00	0.00	0.00	0.00	700.00	1.00	1.00	1.00	$72.14	$0.00	$0.00	3		
69	18	995.54	0.33	664.40	664.40	49.74	0.28	35.60	700.00	0.00	0.24	0.00	700.00	0.95	1.00	1.00	$89.18	$4.46	$0.00	4		
70	22	435.65	0.38	267.95	267.95	423.51	0.32	287.55	555.50	0.00	0.03	0.00	555.50	0.10	0.21	0.21	$39.03	$37.94	$0.00	5		
71	17	395.14	0.26	293.04	293.04	0.00	0.05	0.00	293.04	174.64	0.02	171.62	464.66	0.11	0.11	0.17	$35.40	$0.00	$15.64	6		
72	16	0.00	0.08	0.00	0.00	397.09	0.05	376.44	376.44	66.27	0.02	65.27	441.70	0.00	0.14	0.16	$0.00	$35.57	$5.94	7		
73	21	343.46	0.24	260.01	260.01	400.62	0.00	400.55	660.56	0.00	0.00	0.00	660.56	0.10	0.24	0.24	$30.77	$35.89	$0.00	8		
74	20	733.41	0.02	720.00	720.00	0.00	0.00	0.00	720.00	0.00	0.00	0.00	720.00	1.00	1.00	1.00	$65.70	$0.00	$0.00	9		
75	17	612.20	0.12	540.00	540.00	0.00	0.10	0.00	540.00	0.00	0.03	0.00	540.00	1.00	1.00	1.00	$54.84	$0.00	$0.00	10		
76	12	569.08	0.05	540.00	540.00	0.00	0.05	0.00	540.00	0.00	0.01	0.00	540.00	1.00	1.00	1.00	$50.98	$0.00	$0.00	11		
77	13	706.41	0.24	540.00	540.00	0.00	0.05	0.00	540.00	0.00	0.02	0.00	540.00	1.00	1.00	1.00	$63.28	$0.00	$0.00	12		
78	26	804.47	0.33	540.00	540.00	0.00	0.31	0.00	540.00	0.00	0.06	0.00	540.00	1.00	1.00	1.00	$72.06	$0.00	$0.00	13		
79	32	708.00	0.24	540.00	540.00	0.00	0.05	0.00	540.00	0.00	0.01	0.00	540.00	1.00	1.00	1.00	$63.42	$0.00	$0.00	14		
80	29	861.71	0.37	540.00	540.00	0.00	0.05	0.00	540.00	0.00	0.02	0.00	540.00	1.00	1.00	1.00	$77.19	$0.00	$0.00	15		
81	12	620.73	0.13	540.00	540.00	0.00	0.00	0.00	540.00	0.00	0.00	0.00	540.00	1.00	1.00	1.00	$55.60	$0.00	$0.00	16		

Appendix B. VBA Code Segments

Solver Module

```
Option Explicit
Option Base 1

Dim IncPerf() As Double, Utility() As Double, NIncs As Integer, NMOP As Integer

Sub Solver_Module_Main()
    Dim i As Integer
    RunParametersForm.Show
    Call DeleteRangeNames 'Reset the named ranges
    Call NameRanges 'Name the various ranges used in the model
    Call ResetDecVar 'Resest the contents of the decision variable cell
    For i = 1 To NPoints + 1
        Call UpdateCostTarget(i)
        Call SolverRoutine 'Call the routine to optimize the model
        Call CollectData(i) 'Collect the pertinent data
    Next i
    Call PrintData
End Sub

Public Sub NameRanges()
    With ActiveWorkbook
        With Worksheets("Model")
            Range("K5").Name = "Utility"
            Range("K12").Name = "CostCeiling"
            Range("K13").Name = "CostTarget"
            Range("K14").Name = "DesignCost"
            With Range("A1")
                Range(.Offset(5, 7), .Offset(5, 7).End(xlDown)).Name = "ki"
                Range(.Offset(65, 3), .Offset(65, 3).End(xlDown)).Name = "DesignTotal"
                Range(.Offset(65, 4), .Offset(65, 11).End(xlDown)).Name = "QFDMatrix"
                'Increment 1
                Range(.Offset(65, 13), .Offset(65, 13).End(xlDown)).Name = "Inc1Plan"
                Range(.Offset(65, 14), .Offset(65, 14).End(xlDown)).Name = "Inc1Risk"
                Range(.Offset(65, 16), .Offset(65, 16).End(xlDown)).Name = "Inc1Total"
                Range(.Offset(65, 25), .Offset(65, 25).End(xlDown)).Name = "Inc1RelDA"
                Range(.Offset(65, 28), .Offset(65, 28).End(xlDown)).Name = "Inc1DACost"
                'Increment 2
                Range(.Offset(65, 17), .Offset(65, 17).End(xlDown)).Name = "Inc2Plan"
                Range(.Offset(65, 18), .Offset(65, 18).End(xlDown)).Name = "Inc2Risk"
                Range(.Offset(65, 20), .Offset(65, 20).End(xlDown)).Name = "Inc2Total"
                Range(.Offset(65, 26), .Offset(65, 26).End(xlDown)).Name = "Inc2RelDA"
                Range(.Offset(65, 29), .Offset(65, 29).End(xlDown)).Name = "Inc2DACost"
                'Increment 3
                Range(.Offset(65, 21), .Offset(65, 21).End(xlDown)).Name = "Inc3Plan"
                Range(.Offset(65, 22), .Offset(65, 22).End(xlDown)).Name = "Inc3Risk"
                Range(.Offset(65, 24), .Offset(65, 24).End(xlDown)).Name = "Inc3Total"
                Range(.Offset(65, 27), .Offset(65, 27).End(xlDown)).Name = "Inc3RelDA"
                Range(.Offset(65, 30), .Offset(65, 30).End(xlDown)).Name = "Inc3DACost"
            End With
        End With
    End With
End Sub
Sub UpdateCostTarget(i As Integer)
    Select Case i
        Case Is = 0
            Worksheets("Model").Range("CostTarget").Value = LowBound
        Case Is > 0
            Worksheets("Model").Range("CostTarget").Value = _
                LowBound + (i - 1) * (UpBound - LowBound) / NPoints
    End Select
End Sub

Private Sub SolverRoutine()
    Dim DecVar As Range
    Set DecVar = Union(Range("Inc1Plan"), Range("Inc2Plan"), Range("Inc3Plan"))
    Call ResetDecVar
```

```
    SolverReset
    SolverReset
    SolverOk _
        SetCell:=Range("Utility"), _
        MaxMinVal:=1, ByChange:=Union(Range("Inc1Plan"), Range("Inc2Plan"), _
            Range("Inc3Plan")), Engine:=1, EngineDesc:="Standard GRG Nonlinear"
    SolverAdd _
        CellRef:=Range("Inc1Total"), _
        Relation:=1, FormulaText:=Range("DesignTotal")
    SolverAdd _
        CellRef:=Range("Inc2Total"), _
        Relation:=1, FormulaText:=Range("DesignTotal")
    SolverAdd _
        CellRef:=Range("Inc3Total"), _
        Relation:=1, FormulaText:=Range("DesignTotal")
    SolverAdd _
        CellRef:=Range("DesignCost"), _
        Relation:=1, FormulaText:=Range("CostTarget")
    SolverOptions AssumeNonNeg:=True
    SolverSolve UserFinish:=True
End Sub

Private Sub CollectData(i As Integer)
    Dim j As Integer, k As Integer, _
        c As Range, A1 As Range

    NIncs = 3
    NMOP = 8
    Set A1 = Worksheets("Model").Range("A1")

    ReDim Preserve IncPerf(NPoints + 1, NMOP, NIncs)
    ReDim Preserve Utility(NPoints + 1, NIncs + 1)

    'Capture the utility data
    Utility(i, NIncs + 1) = A1.Offset(4, 10).Value
    For j = 1 To NIncs
        Utility(i, j) = A1.Offset(2, 9 + j).Value
    Next j

    'Capture the relative performance data
    For j = 1 To NMOP
        For k = 1 To NIncs
            IncPerf(i, j, k) = A1.Offset(4 + j, 1 + k).Value
        Next k
    Next j
End Sub

Private Sub PrintData()
    Dim wbCAIV_EA_Data As Workbook, Pathname As String

    Pathname = ThisWorkbook.Path

    Set wbCAIV_EA_Data = Workbooks.Add
    wbCAIV_EA_Data.SaveAs Filename:=Pathname & "\CAIV_EA_Data.xls"
    Application.DisplayAlerts = False
    'Worksheets(1).Delete
    'Worksheets(1).Delete
    Application.DisplayAlerts = True

    Call PrintUtility
    Call PrintRelPerformance
End Sub

Public Sub FindMaxCost()
    Dim c As Range, i As Integer
    i = 1
    Call ResetDecVar
    For Each c In Range("Inc1Plan")
        c.Value = Range("DesignTotal").Cells(i) / (1 - Range("Inc1Risk").Cells(i))
        i = i + 1
    Next c
```

```
    Range("CostCeiling").Value = Range("DesignCost").Value
End Sub

Private Sub FormatDataSheets()
    Dim c As Range, A1 As Range
    Set A1 = ActiveSheet.Range("A1")
    With Range(A1, A1.End(xlToRight))
        .Font.Bold = True
    End With
    With Range(A1.Offset(1, 0), A1.Offset(1, 0).End(xlDown))
        .NumberFormat = "$0.00"
    End With
    With Range(A1.Offset(1, 1), A1.Offset(1, 1).End(xlDown).End(xlToRight))
        .NumberFormat = "0.000"
    End With
    A1.CurrentRegion.Columns.AutoFit
End Sub

Private Sub PrintUtility()
    Dim A1 As Range, i As Integer, j As Integer, k As Integer

    'Print the utility data to the CAIV_EA_Data workbook
    Workbooks(2).Worksheets(1).Name = "Utility Data"
    Set A1 = Worksheets("Utility Data").Range("A1")
    'Column headings
    For j = 0 To NIncs + 1
        Select Case j
            Case Is = 0
                A1.Value = "Cost"
            Case 1 To NIncs
                A1.Offset(0, j).Value = "Increment " & j
            Case Is = NIncs + 1
                A1.Offset(0, j).Value = "Overall"
        End Select
    Next j
    'Column contents
    For i = 1 To NPoints + 1
        A1.Offset(i, 0).Value = LowBound + (i - 1) * (UpBound - LowBound) / NPoints
        For j = 1 To NIncs + 1
            A1.Offset(i, j).Value = Utility(i, j)
        Next j
    Next i

    Workbooks(2).Worksheets(1).Columns(2).Insert
    Workbooks(2).Worksheets(1).Columns("F").Cut (Columns("B"))

    Call FormatDataSheets
End Sub

Private Sub PrintRelPerformance()
    Dim i As Integer, j As Integer, k As Integer, _
        A1 As Range, wsRelPerf As Worksheet

    Workbooks(2).Activate

'Create relative performance data sheets and dump data into the appropriate cells
    For i = 1 To NIncs
        Set wsRelPerf = Worksheets.Add(after:=Worksheets(Worksheets.Count))
        wsRelPerf.Name = "Rel Perf - Inc " & i
        Set A1 = ActiveSheet.Range("A1")

'Create the column headings
        For j = 0 To NMOP
            Select Case j
                Case Is = 0
                    A1.Value = "Cost"
                Case Is > 0
                    A1.Offset(0, j).Value = _
                        Workbooks(1).Worksheets(1).Range("A1").Offset(4 + j, 1).Value
            End Select
        Next j
```

```
'Enter the column contents
        For j = 1 To NPoints + 1
            A1.Offset(j, 0).Value = LowBound + (j - 1) * (UpBound - LowBound) / NPoints
            For k = 1 To NMOP
                A1.Offset(j, k).Value = IncPerf(j, k, i)
            Next k
        Next j

        Call FormatDataSheets
    Next i
End Sub
```

Bibliography

Aldridge, E.C. Pete., Under Secretary of Defense for Acquisition, Technology, and Logistics. Address to Commission on the Future of the United States Aerospace Industry. Arlington, VA. 27 November 2001.

Aldridge, E.C. Pete., Under Secretary of Defense for Acquisition, Technology, and Logistics. Memorandum for Secretary of the Navy. "Cost-as-an-Independent Variable and Spiral Development Implementation Plans." Washington, DC. 19 January 2002.

Aldridge, E.C. Pete., Under Secretary of Defense for Acquisition, Technology, and Logistics. Memorandum for Secretaries of the Military Departments. "EA and Spiral Development." Washington, DC. 12 April 2002.

Ansari, Shahid L. and Jan E. Bell. *Target Costing: The Next Frontier in Strategic Cost Management.* Chicago: Irwin Professional Publishing, 1997.

Boehm, Barry and Wilfred J. Hansen. *Understanding the Spiral Model as a Tool for EA*. Report to Carnegie Mellon University Software Engineering Institute. Pittsburgh, PA. January 2001.

Department of the Air Force. *Command and Control*. Air Force Doctrine Document 2-8 (Draft). Washington: HQ AF/CC, November 1999

Department of the Air Force. *EA for C2 Systems*. Air Force Instruction 63-123. Washington: SAF/AQI, 1 April 2000.

Department of the Air Force. *Air Force EA Guide* (Draft). Washington: SAF/AQ, November 2000

Department of the Air Force. *Region Air Operations Center / Air Defense Sector 'Stop Gap' Project: Technical Requirements Document* (version 1.0). Boston: ESC/ACMB, April 2002.

Department of Defense. *Operation of the Defense Acquisition System*. DOD Instruction 5000.2. Washington: GPO, 4 January 2001.

Department of Defense. *Dictionary of Military and Associated Terms*. Joint Publication 1-02. Washington: GPO, 12 April 2001

Department of Defense. *Mandatory Procedures for Major Defense Acquisition Programs and Major Automated Information System Acquisition Programs*. DOD Regulation 5000.2-R. Washington: GPO, 10 June 2001.

Department of Defense Systems Management College. *Joint Logistics Commanders Guidance for Use of EA Strategy to Acquire Weapon Systems*. Virginia: Defense Systems Management College Press, June 1998.

Fung, R.Y.K., J. Tang, Y. Tu, and D. Wang. "Product Design Resource Optimization Using a non-linear Fuzzy Quality Function Deployment Model," *International Journal of Production Research*, 40: 585-599 (No. 3). 2002.

Guinta, Lawrence R. and Nancy C. Praizler. *The QFD Book – The Team Approach to Solving Problems and Satisfying Customers Through Quality Function Deployment*. New York: Amacom, 1993.

Heuttner, Charles H. "About the Commission on the Future of the United States Aerospace industry." Excerpt from unpublished article. n. pag. http://www.aerospacecommission.gov/quick_facts.html. 24 June 2002.

Kaminski, Paul. Under Secretary of Defense for Acquisition and Technology. Memorandum for Distribution. "Reducing Life Cycle Cost for New and Fielded Systems." Washington, DC. 4 December 1995.

Kaye, Michael A., Mark S. Sobota, David R. Graham, and Allen L. Gotwald. "Cost as an Independent Variable: Principles and Implementation," *Acquisition Review Quarterly*, 353-372 (Fall 2000).

Law, Averill M. and W. David Kelton. *Simulation Modeling and Analysis: 3rd Edition*. Boston: McGraw Hill, 2000.

Lorell, Mark, Julia Lowell, Michael Kennedy, and Hugh Levaux. *Cheaper, Faster, Better? Commercial Approaches to Weapons Acquisition*. MR-1147-AF. Santa Monica: RAND, 2000.

Lorell, Mark and John C. Graser. *An Overview of Acquisition Reform Cost Savings Estimates*. MR-1329-AF. Santa Monica: RAND, 2001.

Luman, Ronald R. "Upgrading Complex Systems of Systems: A CAIV Methodology for Warfare Area Requirements Allocation," *Georgia Institute of Technology 2nd Conference on the Economics of Test and Evaluation*. n. pag. Atlanta, GA. 3 November 1999.

Menon, Unny. *Concurrent Engineering – Concepts, Implementation, and Practice*. London: Chapman and Hall, 1994.

Mullins, Terry. "Systems Management and Production Laboratory CAIV Model." Excerpts from internet web page. n. pag. http://smaplab.ri.uah.edu/caiv. 1998.

Ragsdale, Cliff T. Spreadsheet Modeling and Decision Analysis: 3rd Edition. Cincinnati: South-Western College Publishing, 2001.

Rush, Benjamin C. "Cost as an Independent Variable: Concepts and Risks," *Acquisition Review Quarterly*, 161-172 (Spring 1997).

Tecolote Research, Inc. "CAIV 'How-to' Guide." Excerpt from Automated Cost Estimating Integrated Tools product support information web page. n. pag. http://www.aceit.com/Download/Acrobat/how2caiv.pdf. 2002.

Thurston, Deborah L. and Scott K. Essington. "A Tool for Optimal Manufacturing Design Decisions," *Manufacturing Review*, 6: 48-59 (No. 1).

Thurston, Deborah L. and Angela Locascio. "Decision Theory for Design Economics," *The Engineering Economist,* 40: 41-71 (No. 1).

Wollover, David R. "Quality Function Deployment as a Tool for Implementing Cost as an Independent Variable," *Acquisition Review Quarterly*, 315-338 (Summer 1997).

Vita

Captain Marc T. Lewis entered the United States Air Force in June 1994 after acceptance to the USAF Academy. In addition to holding several key cadet leadership positions, he was a freefall parachuting instructor, jumpmaster, and member of the academy's "Wings of Blue" parachute team. Marc was commissioned in May 1998 and was recognized as a Distinguished Graduate with a Bachelors of Science degree in Biology.

Captain Lewis' first commissioned assignment was as a project officer working in the Ground Theater Air Control System (GTACS) program office, Electronic Systems Center, Hanscom AFB, MA. During this time he managed the development of the Theater Air Defense Missile Tracking System (TADMTS) upgrade to the Air Force's AN/TPS-75 ground-based long range surveillance radar. Later, he served as the executive officer for the Combat Air Forces Command and Control Systems (CAFC2) program office.

In August 2001, Captain Lewis began graduate studies in cost analysis at the Air Force Institute of Technology, Wright Patterson Air Force Base, OH. Upon graduation from AFIT, he will be assigned as an analyst at the Air Force Cost Analysis Agency in Arlington, VA. Marc's research interests include modeling decision systems, cost risk analysis, and simulation.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 074-0188*

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of the collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to an penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From – To)*
25-03-2003	**Master's Thesis**	Jan 2002 – Mar 2003

4. TITLE AND SUBTITLE

INTEGRATING COST AS AN INDEPENDENT VARIABLE ANALYSIS WITH EVOLUTIONARY ACQUISITION – A MULTIATTRIBUTE DESIGN EVALUATION APPROACH

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Lewis, Marc T., Captain, USAF

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S)

Air Force Institute of Technology
Graduate School of Engineering and Management (AFIT/EN)
2950 P Street, Building 640
WPAFB OH 45433-7765

8. PERFORMING ORGANIZATION REPORT NUMBER

AFIT/GCA/ENV/03-05

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

ESC/AC (AFMC)
Attn: Ms. Michelle Rogers, GS-14
50 Griffiss St DSN: 478-1186 x8287
Hanscom AFB, MA 01731 e-mail: michelle.rogers@hanscom.af.mil

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Guidance from the Under Secretary of Defense for Acquisition, Technology, and Logistics (USD(AT&L)) requires 100 percent of defense programs to incorporate cost as an independent variable (CAIV) and evolutionary acquisition (EA) plans within their management baselines. This research endeavors to create a decision tool to assist the DoD acquisition community in satisfying the intent of the USD(AT&L) guidance. Using multiattribute design evaluation techniques, a core CAIV model is formulated. Next, the core model is expanded to incorporate the dominant features of EA. The expanded model seeks to optimize overall utility across a horizon of multiple development increments. Additionally, technical risk factors are integrated to discount the realized level of attainment for design attributes. Using a notional DoD command and control system as the case study, the fully formulated CAIV/EA model is implemented and hosted in a PC spreadsheet application environment. An optimization application is called upon to solve the mathematical program for a series of cost constraints. The resulting data is then collected and translated into a variety of graphical products. Sensitivity analysis is performed to understand the response caused by variations in model's parameters. Model limitations are discussed and recommendations for further investigation are presented.

15. SUBJECT TERMS

Cost as an Independent Variable, CAIV, Evolutionary Acquisition, EA, Acquisition Reform, AR, Multiattribute Design Evaluation, Multiple Objective Decision Analysis, Trade-off Analysis, Utility Theory, Utility Analysis, Quality Function Deployment, QFD, Commercial-Military Integration, CMI, Spreadsheet Modeling

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
					Michael A. Greiner, Maj, USAF (AFIT/ENV)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(Include area code)*
U	U	U	UU	122	(937) 255-3636, ext 4588; e-mail: Michael.Greiner@afit.edu